EXPERIMENTAL ENGINEERING.

Vol. II.

MATERIALS.

EXPERIMENTAL ENGINEERING.

VOL. II.

A Treatise on the Methods and Machines Used in the Mechanical Testing of Materials of Construction.

BY

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PREFACE.

THE systematic testing of the materials used in all classes of engineering work is becoming so general that little apology is needed for the existence of this book; and it is hoped that it will be found helpful, both to young engineers, who have opportunities of using the various appliances described, and also to older men who have, in the ordinary course of their practice, to make use of some of the materials referred to.

Though there may be a slight want of homogeneity in some parts of the book, the author has tried to place the chapters in proper sequence, and take the reader from the early mechanical principles involved in testing work, through the description of the appliances and methods used, to standard results of tests, both general and for specific materials. Too much detail has not been attempted in describing the testing operations; a complete working knowledge can only be obtained by intimate personal contact with the work and a considerable amount of actual practice.

Reference has been made to most of the publications relating to the subject, and the author desires to acknowledge his indebtedness, and express his sincere thanks, for much valuable help gained from Prof. Unwin's "Testing of Materials of Construction," as well as from the two standard works on the same subject by Profs. Thurston and Johnson; to Mr. J. Hartley Wicksteed, of Leeds, for much helpful advice; to Prof. Ewing of Cambridge, my friend, Mr. F. Grover of Leeds, Prof. Stanton of Bristol, Dr. Wilson of Owens College, and

Mr. Charnock of Bradford, for many of the test results and illustrations; to the valuable works of Messrs. Kirkaldy, Spretson, Skelton, Anderson, Butler, and Barlow, as well as to the Minutes of Proceedings of the Institution of Civil Engineers, the Iron and Steel Institute, the Institution of Mechanical Engineers, British Association, American Institutes of Civil and Mechanical Engineers, and the Manchester Literary and Philosophical Society; to the engineering periodicals; "The Mechanical Engineer," "Engineering," "The Engineer," and "Industries"; and, lastly, to the following firms for the loan or gift of blocks for illustration: Messrs. J. Buckton & Son, Leeds; Messrs. Greenwood & Batley, of Leeds; Messrs. Daniel Adamson & Co., Hyde; Messrs. Charles Churchill & Co.; Messrs. Nalder Bros.; Messrs. Sir W. H. Bailey & Co., Salford; and Messrs. Riehlé Bros., Philadelphia.

W. C. P.

20, Kennedy Street,
Manchester, *January*, *1901*.

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ERRATA.

Page 2, end of tenth line—omit word "to."

,, 19, last line should read—$S = f_t = f_c = f$.

,, 22, last line but three should read—

$$T = \frac{\pi\phi}{2} \cdot \frac{G \cdot r^4}{l}.$$

,, 37, bottom formula at bottom of fifth column should be—

$$\frac{W \cdot l^3}{384\,E \cdot I}.$$

,, 147, tenth line should be E = 12,880 tons per square inch.

,, 237, ninth line—Deely should be Deeley.

INTRODUCTORY.

In all engineering works, whether they be of masonry, timber, concrete, or metal, the question of strength is one of the most important which has to be considered; and where any material is to be so placed in a structure as to have to withstand considerable stress, some previous knowledge of the strength properties of this material must be within the reach of the engineer who contemplates its use.

In every engineering structure there are two distinct points with regard to its strength which must be aimed at. These are that, in the first place, the structure must be of ample strength to withstand any and all loads to which it may be subjected without permanent injury to its parts; and, secondly, that there should be no more material employed in any one part than is sufficient to ensure the fulfilment of the first condition. The chief reason for this latter condition is sufficiently obvious—it is simply a question of cost. But, apart from pounds, shillings, and pence, it is obvious that to introduce any such beyond that which is necessary to ensure safety and efficiency would be an unwarrantable waste of valuable material; and, further, it is in many instances advisable to reduce the weight of a structure as far as possible, so as to thereby lessen the stresses due to the weight of the structure itself.

In the case of many engineering structures and works it is usual to apply some kind of test load after the completion of the structure, so as to provide a final check on the work before submitting it to its ordinary load. Thus, bridges are often tested in this manner, by putting upon them loads greatly in excess of those to which they may be expected to be subjected in daily use. Again, boilers are treated in a somewhat similar manner, by applying internal hydraulic pressure double, or more than double, the intended working pressure of the steam. There are, however, many structures which cannot be put to

these final tests, owing to the nature of their load and the position of the structures themselves. Examples of such are to be found in roofs and bridges subject to wind pressures. But even if it were possible to apply these after tests in all cases, it would be preposterous to construct a great and costly work entirely by "rule of thumb," and trust to luck that it would be strong enough to withstand the loads which might be applied to it.

Some previous knowledge, both of the loads to which each part of a structure may be expected to have to withstand, and of the strength of the materials forming these parts, is absolutely necessary. In former times, before such a knowledge existed of the strength of the various materials of construction as is now the case, an engineer had to rely to a great extent on his own or other people's experience, and on his own judgment and instinct for the dimensions of the parts of his structures. Such a plan is of necessity still followed out to a great extent, especially in the case of small and unimportant parts, and also very often in timber structures. It is not an uncommon thing in drawing offices to see a draughtsman vary a dimension several times until he thinks "it looks right." This is perfectly legitimate and allowable in many cases, and is, indeed, necessary in such cases, for instance, as the frames of machines and other structures subjected to a great variety of indeterminate stresses, or to very slight stresses, where stiffness alone is necessary. But in large and important structures and pieces of machinery a certain definite plan must be, and nearly always is, followed.

In the first place, the engineer must know what loads his projected structure will have to sustain as a whole, what part of these are live loads, what part dead loads, and if any shocks are to be expected, and of what magnitude.

Secondly, knowing what the loads upon his structure are to be, he must next be able to calculate what will be the effect of these loads in producing stresses in the several parts of the structure, what are the magnitudes of these stresses, and what their nature; that is, whether the stresses are those of tension, compression, bending, or torsion.

Thirdly and lastly, he must have an intimate knowledge of the properties of the materials he intends to make

use of, so as to be properly guided in determining the shape and dimensions of all the parts.

Of these three divisions the first entirely depends upon the knowledge which the engineer may have as to the conditions pertaining to the particular case in question; the second requires calculations depending upon the principles of mechanics, and may be performed by simple arithmetical or algebraic methods, or the problem may be attacked graphically. When these two first conditions have been determined, the last step in the design of the structure may be taken; that is, knowing the stress which may be expected to act on each part, both as to its nature and magnitude, and also knowing what materials are to be used, the engineer can at once proceed to ascertain the form and dimensions of this part, provided he is fully acquainted, or has some means of becoming acquainted, with the strength properties of the materials. It is towards the fulfilment of this last mentioned condition that the "testing of materials" is undertaken.

For such a case as we have just considered, it is usual to test several small samples of the material to be employed, as in the case of a strip of steel cut from a boiler plate, on the assumption that the whole of the material is uniform and similar in its properties to the specimens tested, or, as in the case of a chain or rope, to subject an actual piece of the work itself to the test. Such tests have been called "commercial tests," and may be either specially made in connection with the structure in question, or have been previously made on some samples of similar material. Besides tests of materials carried out for purely commercial and constructive purposes, there is a great deal of work being done at the present time, and has been done in the past, of a more refined and scientific character, with the intention in most instances, of elucidating the more hidden and complex phenomena displayed by materials under various stresses and under different conditions of stress. Such research has been going on for many years, and is going on most actively at the present time. The knowledge obtained in this way is to a great extent permanent, and though as time goes on more facts are constantly being unearthed with regard to the strength properties of materials, still these new facts are not, as a rule, such as to render unimportant the knowledge already gained, although it is certainly so in some cases. The value of this scientific or research testing may not be at

once apparent, but every test and experiment made in this way is going to help to build up a more complete knowledge of the mechanical properties of all the known materials.

There is another branch of testing that comprises within its limits both those already mentioned, namely, the testing carried on for purely educational purposes. Most of the colleges or departments of colleges devoted to the scientific education of engineering students possess some kind of a testing laboratory. Here, in these laboratories, the students are taught by personal instruction and actual experience to make tests of various materials, and in this way they are not only enabled to learn the details of the appliances used, and the methods and systems employed, but their faculties of observation are called into play, and the properties of the materials they are dealing with are brought home to them in a manner not possible by mere description and the study of books. The number and completeness of the engineering laboratories at technical schools and colleges is increasing year by year, and this is as it should be, for no branch of the scientific education of a young engineer is of greater help to him in after life than the time spent in laboratory work.

In the following chapters it will be the aim of the author not only to describe the various testing appliances and methods as used in purely commercial work, but, at the same time, to make these descriptions applicable to the work of an engineering student.

It has been stated that testing can, according to the apparatus and methods employed, be divided into *commercial* and *scientific* testing. These two are not necessarily quite distinct and apart; in many cases they overlap, but, generally speaking, the methods of commercial testing are more crude, and the measuring appliances used not of so refined and delicate a character as many of those used in purely research testing, which partakes more of the nature of physical laboratory work. In commercial testing, certain standards are usually fixed by purchasers of materials and by certain competent authorities, such as the Board of Trade and Lloyd's, and in the tests to which they are subjected the specimens are expected to exhibit such properties as are required in order to comply with the standards and regulations laid down. In making a commercial test, therefore, it is necessary to know what properties must be specially observed, so that

it may be determined whether the tests do satisfy the requirements, and then to apply such and only such tests as may be needful for the purpose.

In scientific testing the case is different. The observations in a test are generally greater in number, more accurately made with apparatus of greater precision, enabling the observer to see more deeply, as it were, into the phenomena exhibited during the tests.

All testing requires a considerable amount of skill, experience, and sound judgment in its execution, and to these should be added some knowledge of mechanics, so far as the "strength of materials" is concerned. System and order should be rigidly adhered to, both in the carrying out of tests and in the manipulation and presentation of the results. Every detail should be most carefully watched and attended to, as one mistake may render useless a test or even a whole series of tests. Nothing is of more importance than a correct idea of perspective so far as accuracy is concerned, and a clear knowledge of the necessary limits of accuracy to be aimed at, and which are possible in the various kinds of work undertaken, should be most carefully cultivated. Useless attempts at extreme accuracy, where extreme accuracy is neither necessary nor possible of attainment, are always absurd, and in some cases actually mischievous.

The variety of material which is tested, or capable of being tested, is very great.

At the present day most engineering structures, whose design is governed by considerations of strength, are constructed of either iron or steel. These metals have asserted their pre-eminence in such work by reason of their combining the advantages of cheapness, strength, and durability to an extent not found to exist in the case of any other material. The kinds of structures built of iron and steel are very numerous. In addition to the bulk of machinery used for purposes of manufacture, the engines which give the motive power to this machinery, and the shafting and gearing which serve to transmit the power from the engines to the machinery; in addition to their use in formation of structures such as these, iron and steel are greatly used for what, in one sense, are more important works. By these are meant structures whose collapse or failure would endanger human life. Of course, this possibility exists in the case of most machinery of any size, but it is especially evident in such structures as bridges,

boilers, railway appliances, and steamships. In most of these strength is of the first importance, although considerations of form do in most cases affect the design. In addition to iron and steel there are other metals in use for engineering purposes, although, in these, other qualities rather than strength render their use desirable. Such are copper, brass, gun-metal, tin, zinc, lead, aluminium, and various anti-friction alloys. Of these there are several where considerations of strength do enter largely into their use. For instance, copper is used for boiler fire boxes, stays, steam pipes, and for overhead electrical conductors where it has to withstand great tensile loads; gun metal also is often used in machine and engine parts where it has to undergo considerable tension or compression. The increasing use of aluminium and its alloys makes it necessary for its strength properties to be known; and lastly a knowledge of the compressive strength of anti-friction alloys in bearings is often needed.

Timber is used to a great extent in constructive work, especially for temporary work. It is, however, too uncertain a material to allow structural parts to be designed with the same certainty that exists in the case of the metals, without the use of a large margin of safety. Still, tests of timber, although approximate in character, are often necessary and useful, and give reliable information when properly carried out and judiciously applied.

Last among the materials of construction which are tested are those substances which are employed in works of masonry and those of a like nature, chief among these being the different kinds of natural stone, bricks and terra-cotta, cements and limes, and these combined with other substances to form the various kinds of concrete which are used. So much depends on the strength and reliability of these, which are very largely used in the case of buildings, retaining walls, bridges, foundations, and harbour works, and so great is the variation in quality of apparently similar substances, that they present a large field for testing operations.

It will be clear from what has been said that the variety of substances which are subjected, or may be subjected, to tests is very great, and not only do these many substances used in constructive work present many differences in their qualities and behaviour under test, but there are many ways in which any given substance may be tested. Take for example mild steel. It may be used for boiler

plates, when its behaviour under a tensile test becomes important; if for the rivets of the same boiler, its shearing strength should be known; it may be used in the manufacture of pillars or struts, when its compressive strength is required to be known; or, it may be that the steel is required to construct a propeller shaft of, when its properties under a test in torsion are necessary.

And so it is all through. As a rule, it is not sufficient to know the general strength properties of a substance, but the properties which exhibit themselves under special circumstances and when made of special forms, must also be known, and the tests applied should always be judiciously selected and carried out, so that the actual conditions of use may be as nearly as possible satisfied.

In making a study of the subject of testing, it is necessary that the reader should in the first place have some knowledge of that part of the science of mechanics which deals with stresses and strains of various kinds, as such a knowledge is absolutely necessary in reducing the results of many of the tests and experiments he will have to perform. It has, therefore, been assumed by the author that the reader of this book does not approach the subject as an absolute novice to the subject. At the same time a chapter will be devoted to what is little more than a summary of the principal problems which have to be attacked when dealing with the phenomena displayed by bodies under various stresses. In this will be explained briefly the chief of the principles involved, and such formulæ as are required will be given. It is, however, of the utmost importance that a mere carrying out of experiments, and calculating the results from the formulæ given, will be of very little service to the student. He should have nothing to do with an experiment unless he is perfectly clear in his own mind as to all the principles involved.

It will be seen that following on the chapter which has just been mentioned, the various testing appliances are described, the methods employed in carrying out all the principal branches of testing, and the behaviour of the different materials of engineering under stresses of various kinds, is considered so far as is possible within the narrow limits of such a work as this.

It seems hardly necessary to repeat what has already been said, namely, that in all testing work, neatness, order and systematic working and booking should be strenuously

cultivated, along with the actual art of manipulation and observation. All actual observations should be carefully and neatly booked as a test proceeds, for nothing tends so much towards the nullification of test results than careless and inaccurate notes. Such notes ought always to be preserved in a fairly legible state, so that reference can easily be made to them at any time after the test has been made.

To the student of engineering, as well as to the engineer, the preservation of such notes will almost always prove of great service at future times, when he may be very glad to turn to this storehouse of his for what may be most valuable pieces of information. Careful note should be taken of any tests which may be unusual and specially interesting.

CHAPTER I.

THE MECHANICS OF BODIES UNDER TEST LOADS.

1. Before entering upon a description of the appliances and methods employed in the testing of materials, it will be convenient and useful to discuss at some length the phenomena which display themselves, or may be expected to do so, in bodies which are acted upon by forces.

In the first place it must be assumed that all bodies considered are solid and homogeneous. These are both only relative terms, so far as the ordinary substances of daily life and commerce are concerned. A certain tendency to exhibit faint signs of some of the properties of a liquid often manifests itself in solid bodies, as, for instance, this tendency is made practical use of in the manufacture of lead pipes where the metal is compelled, by the application of great pressure, to actually flow through an annular die, and in this way to form a continuous pipe. Then, again, as to a substance being homogeneous. By this is meant that every part of the substance, even the most minute, has the same composition and physical properties as every other part. This is true in a general sense of most of the materials dealt with in testing operations, but strictly speaking, all the substances lack true homogeneity, and there are always small differences in different parts, which tend to manifest themselves under delicate tests. For all practical purposes we can regard most of the bodies dealt with in testing as homogeneous. In this chapter, therefore, we assume perfect homogeneity to exist.

2. **Elasticity and Plasticity.**—All bodies, if acted upon by force, undergo some kind of deformation, no matter what their shape, substance, or size may be. Thus, for example, take the case of a solid prismatic piece of indiarubber; if one end be fixed and a weight hung at the other, the indiarubber will suffer a change of shape, that is to say, its length will be increased and its lateral dimensions diminished; in other words, by reason of the force applied in the shape of the weight, the piece of indiarubber will have undergone a deformation. The body may be of any

shape, and the force applied in any manner, still, a deformation will follow.

It is very important to notice that the deformation so produced must be of one of two kinds. If a deformation follows a force applied, and if after the deforming force has been removed the body returns to its original dimensions the deformation is said to have been *elastic*. On the other hand, if, after removing the deforming force, the body still retains its deformed condition, it is said to be to some extent *plastic*. In what follows here, the behaviour of bodies under both conditions will be dealt with.

The materials of construction all exhibit these two properties of elasticity and plasticity to a more or less marked degree. It may be stated that no material of construction is perfectly elastic, nor is any substance perfectly plastic. In most of the materials elasticity is practically maintained as the force continues to be increased up to a certain point, called the *elastic limit*, and after this point has been reached and passed the body becomes partially plastic, and elasticity approximately ceases.

In case of the other materials, such as cement and masonry, the properties of elasticity and plasticity do not exhibit themselves to anything like so marked a degree as they do in the case of the metals, but still, by means of delicate appliances, these properties may be detected, though only in a small degree. When forces are applied to such materials, the tendency is, if these forces are sufficiently great, to cause rupture, crumbling, and disintegration of the substance.

3. Stress and Strain.—Where bodies and materials are employed in the formation of works of construction they are subjected to what are called *stresses*, the stress upon a body arising from either a force or a system of forces. Stresses may be of various magnitudes, and may be produced by the weights of the structures themselves in which they occur, or by causes which are external to the structure.

The result of the action of a *stress* upon a body is always to produce a *strain*, which is a deformation of the body. If the deformation only exists so long as the force is acting, the strain is elastic; if the deformation remains after the removal of the stress, the strain is plastic. For instance, if a piece of indiarubber be pulled by a longitudinal stress, it will be elongated, and when the force is removed the indiarubber will return to its original

dimensions; but, if a lump of moist clay be squeezed so as to change its shape, on the removal of the squeezing force there will be no springiness or tendency to return to its former shape.

The semi-plasticity of metals is made great use of in the trades, as has already been pointed out. Wire is drawn, hot iron and steel are forged, copper is beaten, and all manner of small parts are formed from cold metal by stamping. This property in the metal is called its capability for taking "permanent set."

4. External and Internal Stresses.—If a body is acted upon by any stress or system of stresses whatsoever, the stresses so acting upon the body, and which are due to causes outside the body, are termed *external stresses;* they produce by their action certain effects within the internal structure of the substance, tending to interfere with its molecular arrangement; these are the "internal stresses" brought about by the "external stresses."

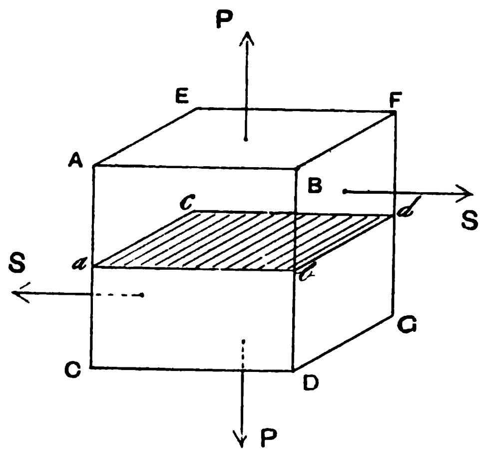

FIG 1.

In Fig. 1. A B C D is a cube. If a force P be applied normal to one of its faces A E F B, and an equal and opposite force also axially and normal to the opposite face C G D, both forces acting away from the cube, a stress in *tension* or *tensile stress* is said to be applied, and its tendency is to cause rupture of the cube across some section, such as *a b c d* at right angles to the direction of the force, the force exerted on this section balancing the pull of the external force P. The area of the section

a b c d being A, then the stress, in units of force per unit of area, is

$$f_t = \frac{P}{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (I.)$$

Thus we can talk of the *force,* or *load,* on a section, but the stress is the *intensity of the force* or the *force per unit area.* For instance, a metal bar whose cross-section is 4 sq. in. may be subjected to a tensile load of 20 tons; the *load* on the bar is 20 tons, but the *tensile stress* is

$$\frac{20}{4} = 5 \text{ tons per sq. in.}$$

Again reverting to Fig. 1, if the force P, instead of acting away from, acted towards the cube, it would then be called a *compressive load,* and its tendency would be to cause failure by crushing. In this case also the *compressive stress* is

$$f_c = \frac{P}{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (II.)$$

P in this case having the opposite direction.

Suppose, now, that the two forces S, S, were to act on the cube in such a way as to cause the upper half above the section to slide across the lower half, as shown, these forces would be called *shearing forces,* and would produce a *shearing,* or *tangential* stress on the section in question. The magnitude of this stress would be

$$f_s = \frac{S}{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (III.)$$

These stresses which have been mentioned are termed *simple stresses.* They are generally expressed as so many *tons* or *pounds* per *square foot* or *square inch,* the pound weight and its multiple the ton weight being the units of force which are found most convenient and suitable for engineering work.

5. Compound Stresses.—In addition to these simple stresses there are a number of cases of compound stress which occur frequently in parts of structures. Those most often met with are the stresses in *bending, torsion,* and *combined bending and torsion. Bending* is exhibited in its simplest form on Fig. 2. A load W is supported in the

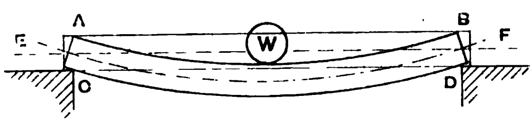

FIG. 2.

middle of a beam whose ends rest upon two supports. Previously to the application of the load the beam was straight. On the application of the load the beam is made to curve downwards and a *bending stress* is said to be produced. The result of the bending is to shorten the upper surface A B, and stretch or elongate the lower one C D. Consequently A B is in *compression* and C D in *tension*. The greatest intensity of each stress is at the outer surface, and it diminishes gradually to zero as the centre is approached. This surface of no stress is called the *neutral surface*. It will be seen that a bending stress is a combination of *tension* and *compression*.

Torsion is not, strictly speaking, a compound stress, but a particular case of shearing stress. The meaning of torsion is shown on Fig. 3. A circular bar (the bar need not necessarily be circular) is acted upon by two equal and opposite couples, or pairs of moments, one at either end.

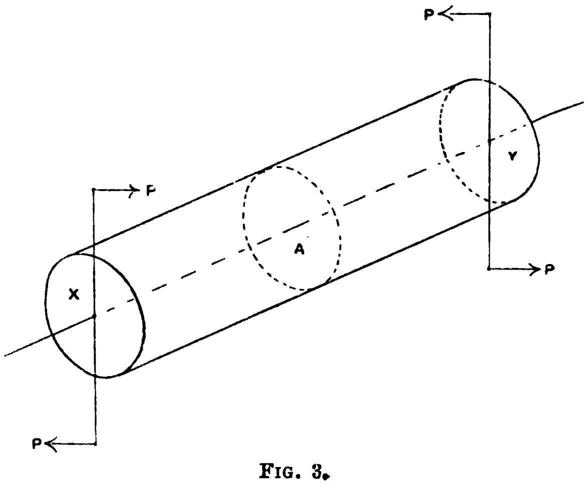

FIG. 3.

That at the left-hand end, X, tends to twist the bar in a right-hand direction, while that at Y has an opposite effect. The result is that the right-hand half of the bar tends to twist or slide in a circular direction about its own axis, with respect to the left-hand portion; and there is a *torsional stress* exerted across a section A. The difference between this and simple shearing is that the latter takes place in straight lines, in the former it is rotary, and the parts of the section near the circumference have a greater movement than those nearer the axis, and conse-

quently the stress is greater at the circumference, and gradually diminishes until it becomes zero at the axis.

Combined Bending and Torsion is a case that often occurs in practice, but which is not often applied in testing operations. It occurs in such cases as the overhung crank-shaft of a steam engine, where the shaft is subjected to the twisting moment exerted at the crank pin, and a simultaneous bending moment due to either the weight of the flywheel or to thrust of the connecting rod, or both.

6. Relation of Stress and Strain on Elastic Bodies.—So far we have only referred to the various stresses themselves, and not to the effect they produce. The results of *stresses* are *strains*. The word "strain" is often, though wrongly, used in the same sense as stress.

When a bar is pulled by a load, the tensile stress acting produces tensile strain, which, in this case, is an elongation of the bar. Similarly, a compressive stress produces a shortening of the bar as its strain; the strain in shear is simply a transverse distortion; that in torsion a circular or spiral distortion. We will consider each case separately.

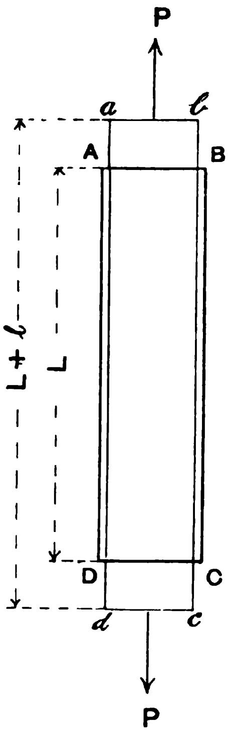

FIG. 4.

7. Tension.—If a rectangular prism ABCD be subjected to a tensile load P, acting along the axis, the stress induced on a section of area A, at right angles to the axis, will be,

$$f_t = \frac{P}{A}$$

The effect of this load is to cause an elongation of the prism. If its original length be L, and the elongation be called l, then the *strain* is expressed by the ratio or fraction $\frac{l}{L}$; and the general relation between the stress and the strain it produces is expressed in Hooke's Law, which says that "the extension of a bar under a tensile load is proportional to the stress;" or,

$$\frac{l}{L} \propto f_t$$

More particularly, we may say that the extension is equal to the stress divided by a constant quantity, or,

$$\frac{l}{L} = \frac{f_t}{E}$$

This quantity E depends only upon the particular material in question and varies with different materials. It is called the Modulus of Elasticity. We can write the last equation in the form,

$$f_t = E.\frac{l}{L}$$

and if we have $l = L$, or, in other words, if the bar is stretched through its own length,

$$\frac{l}{L} = 1 \text{ and } f_t = E.$$

From this we see the modulus of elasticity in another light. It may be said to be the stress which would have to be applied in order to stretch the prism to double its original length. This is, of course, a state of things impossible of achievement in any material of construction, as the limit of elasticity is passed soon after the bar has been stretched beyond about one-thousandth of its length.

8. Compression. — The same relation holds for compression as well as tension, and we have the equation

$$f_c = E.\frac{l}{L}$$

Putting these equations in a more general form, equally applicable to tensions and compressions, we have

$$\frac{f}{E} = \frac{l}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (IV.)$$

or—

$$\frac{\text{The stress applied}}{\text{The modulus of elasticity}} = \frac{\text{The amount of strain}}{\text{The original length of the prism}}$$

9. Poisson's Ratio.—In Fig. 4 if the prism is stretched elastically in an axial direction, it stands to reason that, at the same time it will be diminished laterally, and this is found to be so. If the linear dimensions of the prism are increased to an extent represented by l, and we say that the transverse dimension originally X is diminished to an amount represented by x, the axial or longitudinal strain will be

$$\frac{l}{L} = \theta$$

and the lateral or transverse strain

$$\frac{x}{X} = \phi$$

the ratio of the former to the latter

$$\frac{\theta}{\phi} = m \quad . \quad . \quad . \quad . \quad . \quad (\text{V.})$$

is called Poisson's Ratio. This has a value for solid bodies varying from 3 to 4; for the metals it is very nearly 4.

In the case of indiarubber, so long as the strains are small, the value is about 2.

10. Tangential or Shearing Strain.—When a shearing stress acts on a prism, it is not axially, and upon a section perpendicular to the axis, but transversely in a direction parallel to the section considered.

Thus in Fig. 5, A B is a prism or bar subjected to a shearing stress, brought upon a section at right angles to the axis of the bar. The stress need not necessarily be on such a section, in fact, it may act upon any plane within the material, but the case exhibited here is the one which most commonly occurs in practice, in rivets, knuckle-joints and eye-joints generally.

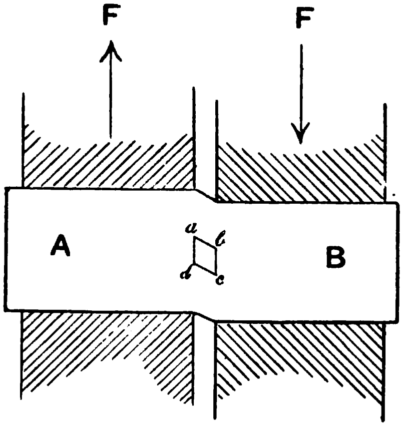

FIG. 5.

The prism A B is supposed to be so constrained that the left-hand portion tends to move bodily upwards, while the tendency of the right-hand portion is to move downwards. If the figure of a square a, b, c, d, be drawn upon the bar, so as to be intersected by the section under stress, when the shearing load F is brought to bear upon the bar, this square will be distorted, so as to assume the form of a rhombus, as shown in the figure. A clear understanding of what actually takes place in the case of a shearing stress will be obtained by a consideration of the case exhibited on Fig. 6; here A B C D is a prism

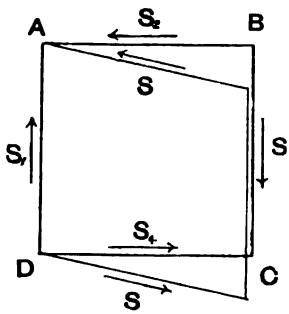

FIG. 6.

or cube whose end is distorted into the form of a rhombus, as has been shown in the case already mentioned (Fig. 5).

Under the shearing stress upon it the prism becomes simply distorted from A B C D to A *b* *c* D, (Fig. 7), the sides remaining of the same length and parallel, and the diagonal D B being shortened and A C lengthened. In order that this distortion may occur four equal stresses S must act tangentially to the sides, as shown. The result of these stresses will be a distortion without a perceptible change of volume. The shearing stresses S_1 and S_2 result in forces

$S_2 \times$ A B acting along B A $= F_2$

and $S_1 \times$ D A acting along D A $= F_1$.

Similarly, the other pair of stresses S and S_4 result in forces F_3 and F_4. Combining these, the resultants of F_1 and F_2 will be a force along the diagonal C A; and there will be an equal and opposite force acting along the diagonal in the opposite direction A C.

Thus the effect of the shearing stresses is the same as would be produced by a tensile stress acting along the direction of the diagonal A C.

The total force thus acting along A C, *the side of square being taken as unity* is

$$\frac{S_1}{\sqrt{2}} + \frac{S_2}{\sqrt{2}} = \sqrt{2}\,S,$$

S_1 and S_2 being equal.

Similarly, the pairs S_2, S, S_4, S_1 may again be resolved so that they result in a compressive force along the other diagonal B D. This will, by the same course of reasoning, also be

$$\sqrt{2}\,S.$$

These are the total forces along the diagonals. The tensile stress parallel to A C will be at right angles to D B, and be of intensity

$$f_t = \frac{\sqrt{2}\,S}{\sqrt{2}} = S,$$

and the compressive stress at right angles to the diagonal A C will also be

$$f_c = \frac{\sqrt{2}\,S}{\sqrt{2}} = S.$$

So that it is thus proved that the four equal shearing forces acting *along* the sides of the square are equivalent to two

sets of stresses, one in tension and one in compression, at right angles to the diagonals of the square, and of equal intensity to the shearing stresses.

In the case of tension and compression the ***strain*** is reckoned as the amount the bar is elongated or shortened; in shearing the strain is the angle of distortion, as, for instance, in Fig. 7, the strain is the angle B A b or C D c. E is the modulus of direct elasticity, and is such that

$$E = \frac{f_t}{\frac{l}{L}}$$

In a somewhat similar sense there is a ***modulus of transverse elasticity*** or *modulus of rigidity*, G, such that

$$G = \frac{f_s}{\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{VI.})$$

where θ is the angle of distortion.

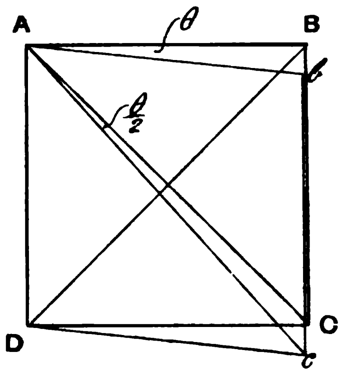

FIG. 7.

The relation which exists between the modulus of direct elasticity E and the modulus of rigidity G may be shown in the following way:—

Let the angle of distortion be small, say θ. It has been shown that when there are four equal shearing stresses acting along the sides of the square, they are equivalent in their effects to those of two direct stresses at right angles to one another acting along the diagonals of the square, and equal to one another in intensity and also to the shearing stresses. Thus, if S is the shearing stress, f_t and f_c the two stresses along the diagonals, one of which is tensile and the other compressive, then

$$S = f_t = f_c$$

When the stresses, S, produce distortion through a small angle θ, θ being measured in circular measure, we have the relation

$$\frac{S}{G} = \theta. \quad \text{This is for shearing.}$$

The equivalent stresses in tension f_t and compression f_c may be considered as producing an elongation of the diagonal A C, causing it to assume a length A c. This elongation is due to the tensile stress acting along and parallel to the diagonal and also to the compressive stress f_c, acting at right angles to this. The combined effect of these is to produce a strain equal to A c − A C. Thus, we have the relation

$$\frac{A\,c - A\,C}{A\,C} = \frac{f_t}{E} + \frac{f_c}{E} \cdot \frac{1}{m}$$

where m is Poisson's Ratio, or

$$\frac{A\,c - A\,C}{A\,C} = \frac{f}{E}\left(1 + \frac{1}{m}\right)$$

$$f_t \text{ being } = f_c = f$$

It will be obvious that, for any distortion, the angle B A b = 2 (angle C A c); or, C A c is $\frac{1}{2}\theta$.

If the extension A c − A C be called q, from the figure it will be seen that

$$q = A\,c - A\,C$$

$$= 2.\ A\,B.\ \cos\left(\frac{\pi}{4} - \frac{\theta}{2}\right) - 2.\ A\,B.\ \cos\frac{\pi}{4}$$

If θ is very small, this expression reduces to

$$q = A\,B.\frac{\theta}{\sqrt{2}}$$

$$\text{and } A\,C = \sqrt{2}\ A\,B;$$

So that

$$\frac{A\,c - A\,C}{A\,C} \text{ becomes } \frac{\theta}{2}.$$

But $$\theta = \frac{S}{G}$$

Therefore we have, finally,

$$\frac{S}{G}\,\frac{1}{2} = \frac{\theta}{2} = \frac{f}{E}\left(1 + \frac{1}{m}\right)$$

$$(S = f_t = f_c = \quad)$$

Wherefore

$$\frac{G}{E} = \frac{1}{2\left(1+\frac{1}{m}\right)} \quad . \quad . \quad . \quad . \quad \text{(VII.)}$$

For metals the value of m is as nearly as possible 4, so that

$$\frac{G}{E} = \frac{2}{5}$$

11. Torsion.—Torsion may be defined as rotational shearing.

If the shaft represented in the figure has its end, marked A, held and rotated by the couple P × 2a, and has its other end held and rotated in the opposite direction by an equal couple P × 2a, the plane of one end will

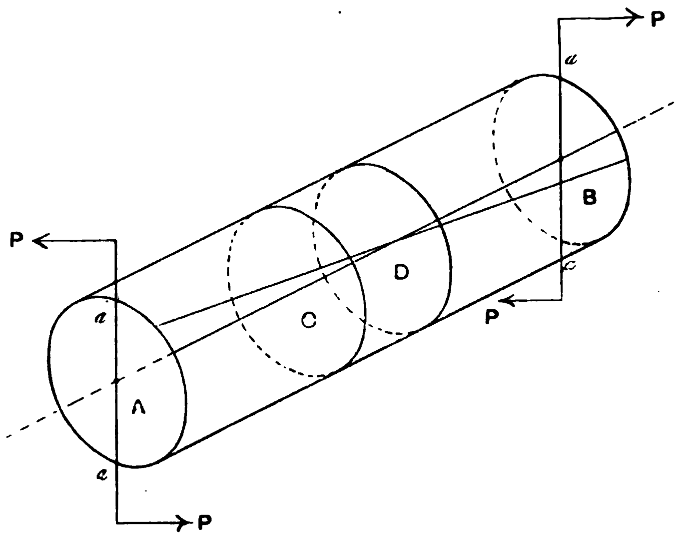

FIG. 8.

revolve, or tend to revolve, with respect to the other end. If the material is elastic, a line drawn on the surface of the shaft parallel to the axis previous to the application of the stresses will be deflected so as to form an angle with its original position, as indicated by the second line. The short portion of the shaft enclosed between the two parallel planes marked C and D is shown on an enlarged scale on the following Fig. 9.

The two planes are rotated, as shown by the arrows (Fig. 8), causing a distortion. A line A B originally parallel to the axis is brought to A C, the angle B A C being called θ.

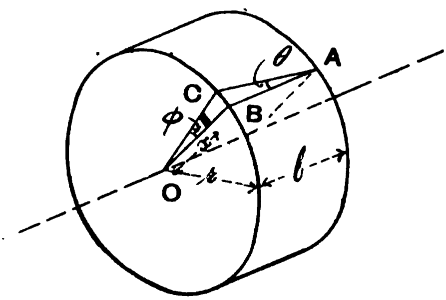

FIG. 9.

This is similar to the angle of distortion of the cube which we have just considered. The radius O B is turned through an angle B O C = ϕ.

Consider a small ring of the circle at a radius x and having a width δx. The whole area of such a strip will be

$$= 2 \pi x \, \delta x$$

The stress on the metal due to the rotation will be a shearing stress on the section of the shaft perpendicular to the axis. The intensity of this stress, unlike the case of simple shearing where it is constant over the whole area, will vary from centre to circumference, and will be proportional to its distance from the axis. If f be the stress at the surface of the shaft and s be the stress at any other radius x, f will be the maximum stress corresponding to the maximum strain, and the intensity of the stress s at x will be

$$s = f \frac{x}{r}$$

r, being the radius of the shaft. Therefore, the total force exerted upon the ring in question will be

$$s. \; 2 \; \pi x. \; \delta x. \, ;$$

and its moment about the axis

$$s. \; 2. \; \pi. \; x. \; \delta x. \; x, \text{ or}$$

$$2. \; \pi \frac{f}{r} x^3 \, \delta \, x$$

Integrating this, we have the external twisting moment

on the shaft as equal to the sum of the moments of the internal forces, or

$$T = \frac{2\pi f}{r}\int_o^r x^3\, dx$$

$$= \frac{\pi}{2} f r^3 . \quad . \quad . \qquad \text{(VIII.)}$$

If we use the diameter d instead of the radius r, the formula becomes

$$T = \frac{\pi}{16}\ f\ d^3 \quad . \quad . \quad . \quad . \quad . \quad \text{(IX.)}$$

Where the shaft is hollow, with the two diameters D and d, we have

$$T = \frac{\pi}{16}\ f\ .\ \frac{D^4 - d^4}{D} . \quad . \quad . \quad . \quad . \quad \text{(X.)}$$

So far we have taken no account of strains. When the short cylinder in the figure is strained by an external twisting moment T, the line A B becomes deflected into a position A C. Call the angle B A C, θ. Now

$$\frac{f}{G} = \theta$$

Let the length of the cylinder be l, and the angle C O B, ϕ. Then, for small deflections

$$\theta = \frac{BC}{l}, \text{ and}$$

$$\phi = \frac{BC}{r}, \text{ therefore}$$

$$\theta = \frac{r}{l}\ \phi = \frac{f}{G}$$

wherefore,

$$\phi = \frac{l}{r} . \ \frac{f}{G}$$

$$\text{From (VIII.) } \phi = \frac{2}{\pi}\ \frac{T\,l}{r^4\,G} . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(XI.)}$$

writing this otherwise, we get

$$T = \frac{\pi}{2} . \ \frac{G.\,r^4}{l} . \quad . \quad . \quad . \quad . \quad . \quad \text{(XII.)}$$

Another useful form is

$$G = \frac{2.\,l.\,T}{\pi.\,\phi.\,r^4.} . \quad . \quad . \quad . \quad . \quad . \quad \text{(XIII.)}$$

$$= \frac{32.\,l.\,T}{\pi.\,\phi.\,d^4.}$$

This last becomes of use in experimental work, where T, l, it, and d are determined from measurements taken, when D is possible to calculate the value of G for the material in question.

For hollow shafts, this becomes

$$G = \frac{2}{\pi} \cdot \frac{l}{\phi} \cdot \frac{T}{(R^4 - r^4)} \quad . \quad . \quad . \quad . \quad (XIV.)$$

$$= \frac{32}{\pi} \cdot \frac{lT}{\phi} \left(\frac{1}{D^4 - d^4} \right)$$

where R and r are the outer and inner radii, and D and d the corresponding diameters.

12. Cubic Elasticity.—This, or as it is often called, elasticity of volume, relates to changes, not of length, breadth, or distortion, but to changes of volume. If a body be subjected to a stress normal to its surface at every point, its volume will be changed, and either increased or diminished. If the original volume of a body is V, and a pressure p be applied to its surface, the volume will be changed by an amount v when

$$\frac{K}{V} = \frac{p}{v} \quad . \quad . \quad . \quad . \quad . \quad . \quad (XV.)$$

K being the *co-efficient of cubic elasticity.*

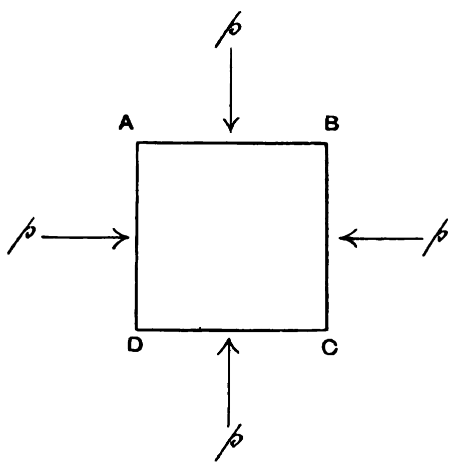

FIG. 10.

Consider the case of a cube acted upon by a uniform stress p, on every face. If L is the length of

side, and l the extension or compression, which would be produced by a longitudinal stress p; then call the strain,

$$\frac{l}{L}=a$$

Now, considering the face ABCD; the effect of the pressures p will be to shorten the square in the direction A'D to an extent

$$\left(a-\frac{2a}{m}\right)$$

the $\frac{2a}{m}$ being due to the retardation of the shortening by the pressures on the other two pairs of faces. The total strain will thus be

$$3\left(a-\frac{2a}{m}\right)$$

and

$$\frac{K}{p}=\frac{1}{3\left(a-\frac{2a}{m}\right)}$$

and as

$$a=\frac{l}{L}=\frac{p}{E}$$

we have

$$K=\frac{p}{3\left(\frac{p}{E}-\frac{2p}{E\,m}\right)}$$

$$=\frac{E\,m}{3m-6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(XVI.)}$$

wherefore

$$m=\frac{K}{E}(3m-6) \quad . \quad . \quad . \quad . \quad . \quad \text{(XVII.)}$$

But

$$E=2G\left(1+\frac{1}{m}\right)$$

Therefore,

$$m=\frac{K(3m-6)}{2G\left(1+\frac{1}{m}\right)} \quad . \quad . \quad . \quad \text{(XVIII.)}$$

which easily reduces to

$$m=\frac{6K+2G}{3K-2G} \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(XIX.)}$$

We have thus three co-efficients of elasticity E, G, and K, and their mutual relations are expressed by the equation just deduced.

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A.E.

$$n_1 = n_2 - \quad 2 ;$$

and the maximum bending moment, M_B, at the centre of the beam, is

$$M_B = \frac{R_1 \cdot l}{2} = \frac{R_2 \cdot l}{2}$$

$$= \frac{W \cdot l}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (XX.)$$

The immediate effect of hanging a weight W on any beam of elastic material will be a downward deflection, as shown in the figure, the upper surface becoming concave, and the lower convex.

In part of the figure (2) the beam is shown before any load has been put upon it, and therefore in a perfectly straight condition. The beam is shown in its side view by the rectangle A B C D. If, now, the load W is hung upon it, a deflection will take place, with the result above described. If the beam had been composed of a number of layers, or laminæ, the effect of the deflection and curvature would have been to simply alter the shape of each separate layer without either lengthening or shortening it. With a uniform elastic beam this is, however, not the case. The beam, as a whole, is curved, its upper layers are shortened, and its lower layers extended. That this is so can easily be shown by making a V shaped notch on the upper surface G (Fig. 11); under the deflection caused by the load this notch will close up and become a parallel slit. Thus the upper parts of the beam are shortened in the bending, and this shortening must be due to a compressive stress. Just in the same way it may be shown that the lower parts are thrown into tension by making a saw cut in the lower surface; this opens under the stress, and becomes a V shaped notch, similar to the one that was made in the upper side of the beam; in fact, the state of things is exactly reversed. It will be further seen that the width of opening at the lower side is greater at the surface and decreases towards zero near the centre, thus showing that the tensile stress is greater at the outer surface on the under side of the beam and zero at the centre; the stress, both the tensile on one side and the compressive on the other, is proportional to its distance from the centre. The part of the beam towards the centre where the stresses each diminish to zero is called the "neutral surface," and the intersection of this with a vertical plane the neutral axis.

The relation between stress, strain, and bending moment for a beam of uniform rectangular section is shown in the following way:—

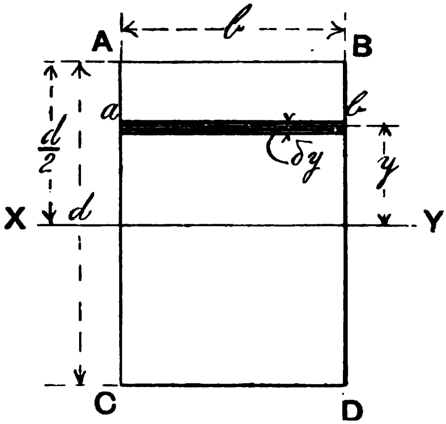


FIG. 12.

Let it be assumed that the beam is of uniform material, whose modulus of elasticity in tension is equal to that in compression. Let the maximum stresses in the metal in tension and compression be f_t and f_c respectively. The section of the beam is shown on Fig. 12 as ABCD. The depth of the beam is d, and its breadth b. Consider a strip of this section at a distance y from, and parallel to, the neutral axis XY. Let this strip have a width δy, and let the stress at this distance from the neutral axis be f_y.

The total stress on the strip will be

$$f_y \,.\, \delta_y \,.\, b,$$

and its moment about the neutral axis

$$f_y \,.\, \delta_y \,.\, b \,.\, y.$$

But this stress f_y is proportional to its distance from XY, that is

$$\frac{f_y}{f_c} = \frac{y}{\frac{d}{2}}, \quad \therefore \; f_y = y \frac{f_c}{\frac{d}{2}}$$

So that the moment of the stress on the strip may be written

$$y \,.\, \frac{f_c}{\frac{d}{2}} \,.\, \delta y \,.\, b \,.\, y = \frac{f \,.\, b \,.}{\frac{d}{2}} y^2 \,.\, \delta y.$$

The sum of all such moments taken over the whole section becomes the integral.

$$\int_0^{\frac{d}{2}} \frac{2}{d} f \,.\, b \,.\, y^2 \, d\,y$$

Integrating, this becomes

$$\frac{2}{3} f_c \quad b \quad \frac{d^2}{8}$$

This is the total moment made up of the sum of all the stresses, varying from 0 to f_c, acting upon all the areas $b \,.\, \delta\, y$, *on one side of* the neutral axis. If we suppose that the elastic properties of the material are the same in tension as in compression, then we shall have an equal moment of resistance on the tension side of the neutral axis. That is to say,

$$\frac{2}{3} f_t \,.\, b \frac{d^2}{8}$$

f_t being equal to $f_c = f$, the total moment of resistance of the metal is the sum of these two, or

$$\frac{1}{6} f\, b\, d^2$$

and this is equal to the moment of the external forces acting on the section. Calling this M_B, we have

$$M_B = f \frac{b\, d^2}{6} \quad . \quad . \quad . \quad . \quad \text{(XXI.)}$$

$$= f\, Z \,. \quad . \quad . \quad . \quad . \quad . \quad \text{(XXII.)}$$

Where Z is what is called the "modulus of the section."

We can go back a step and write the moment again in the form of an integral

$$M_B = \frac{f}{\frac{d}{2}} b \int_{-\frac{d}{2}}^{+\frac{d}{2}} y^2 \, d\,y$$

which may be written in the form

$$M_B = \frac{f}{\frac{d}{2}} \int_{-\frac{d}{2}}^{+\frac{d}{2}} b\, y^2 \, d\,y$$

The integral $\int_{-\frac{d}{2}}^{+\frac{d}{2}} b \; y^2 \; d \; y$ is called the "moment of

inertia" of the section. It is the summation of the products of all small increments of area into the squares of the distances of these areas from the neutral axis.

The moment of inertia is generally denoted by the letter I. If we call the distance of that part of the section furthest from the neutral axis, and therefore under the maximum stress Y, then the above equation becomes

$$\frac{M}{I} = \frac{f}{Y} \quad . \quad . \quad . \quad . \quad . \quad \text{(XXIII.)}$$

Y in the present instance being equivalent to $\frac{d}{2}$. This last equation is perfectly general and applies equally well to sections of all shapes, the moment of inertia varying according to the form of the section.

Here $$M = \frac{f\,I}{Y} \text{ and we have}$$

that $$M = f\,Z, \text{ so that}$$

$$Z = \frac{I}{Y}. \quad . \quad . \quad . \quad . \quad . \quad \text{(XXIV.)}$$

or the modulus of the section is equal to the moment of inertia divided by the distance from the neutral axis to the part of the section furthest away from it.

In working out beam questions which require the use of the moment of inertia, it depends upon what is the form of the section, as to whether the moment of inertia is found by means of ordinary mathematical methods or the more usual formulæ, or whether purely graphical methods must be employed. If the section under consideration is a simple and regular one, then the proper formulæ can be made use of, or the moment of inertia can be calculated *ab initio*. But in cases where the section is irregular or complicated, or both, the use of the following well-known graphic method will save time and trouble.

The principle involved will be best explained by means of a simple example.

A B C D is an ordinary rectangular beam section, with a neutral axis X Y. As before, consider a small strip of the area *a b* taken parallel to the neutral axis. The area of this strip is $b\,\delta y$, and the stress upon it f_y, where

$$f_y = \frac{y}{Y} \cdot f.$$

So that the total force upon this strip is

$$f_y \cdot b . \delta y = \frac{y}{Y} . f . b . \delta y.$$

This can be written, with a somewhat different meaning, as

$$f . \left(\frac{y}{Y} . b . \delta y \right)$$

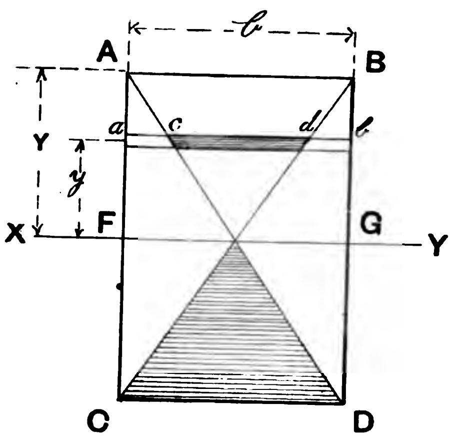


Fig. 13.

or, instead of saying the *total force on the strip* is the *reduced stress f_y multiplied by the whole area $b . \delta y$*, we may say it is the *maximum stress, f, multiplied by a reduced area* $\left(\frac{y}{Y} . b . \delta y\right)$, which comes to the same thing. To obtain this reduced area graphically, it is only necessary to draw straight lines from A and B to the middle point of the neutral axis and they intercept a b in c and d, and the required area is the one shown darkened. If the process be extended to the whole area, a triangle similar to that one shown on the lower half of the beam, is obtained.

This figure, which in this case is a triangle, is called the "modulus figure," for one side of the beam, and it is such that a constant stress f acting upon it would have precisely the same effect as a variable stress acting upon the rectangular section C F G D. The resultant of this constant stress acting upon the various parts of the area passes through the centre of gravity of the modulus figure,

and the modulus Z is the product of the area by the distance of its centre of gravity from the neutral axis. In the case in question, the area of the modulus figure, on one side of the axis, is obviously

$$\frac{1}{2} \cdot b \cdot \frac{d}{2};$$

and the centre of gravity of the triangle is situated $\frac{2}{3} \cdot \frac{d}{2}$ from the neutral axis. So that the modulus of the section, taking both sides of the neutral axis, is

$$2\left(\frac{1}{2}\, b\, \frac{d}{2} \times \frac{2}{3}\, \frac{d}{2}\right)$$

$$= \frac{b\, d^2}{6}$$

which is what we obtained by the previous method.

This principle can be extended to more complex and difficult figures, and will be found of the greatest use for such cases as rail sections, rolled joists and beams, and awkward sections generally.

(a)

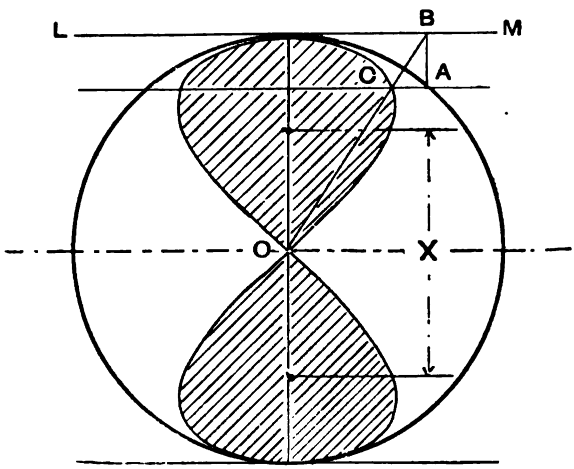


Fig. 14. (a)

On Figs. 14 are shown two examples of these. That marked (a) is a solid circular section; (b) is a section of a

cast-iron beam. The *modus operandi* of finding the modulus figure of a section of any shape is as follows: The figure of the section should be drawn to scale, and this figure should next be cut out in thin cardboard. This cardboard figure can now be balanced on some kind of knife edge in order that the position of its centre of gravity may be found. Through this point a line is placed upon the drawing to represent the neutral axis. Two base lines are now drawn parallel to the neutral axis; if the figure is symmetrical about the neutral axis, the base lines are equidistant from it, and are drawn through that portion of the figure farthest from the axis. If the figure is not symmetrical, the base lines should be still drawn equidistant from the axis, and either at a distance equal to that of the farthest point on one side or the other, as will afterwards be explained. The modulus figure may now be drawn.

A number of lines should be drawn parallel to the neutral axis, intersecting the boundary lines of the figure in a number of isolated points. In (*a*) one of such points is A. To get the corresponding point on the modulus figure, draw A B perpendicular to the base line L M; join B to the centre O, cutting the horizontal line through A in C; then C is the required point on the modulus figure. In this way, by taking in a number of points on the original figure, a number of corresponding points on the modulus figure may be obtained, by a precisely similar construction.

Where the beam section is unsymmetrical, as at (*b*), the distance of the base lines has to be decided according to whether the stress considered is the maximum in tension or the maximum in compression. Thus, if the section is to be that of a beam loaded upon the top side, and supported at both ends, the beam will be carried downwards by the load, and the portion of the section above the neutral axis will be in compression, while that below is in tension. If it is desired to work on the maximum stress allowable in the metal in compression, then the base lines must be drawn at a distance from the neutral axis = C A; if the stress in tension is to be used, as is usually done, the base line distance will be B C = C D. The construction is the same as before.

When the modulus figure has been obtained in the way just described, the two portions, upper and lower, should be cut out in cardboard, balanced about a knife edge in two positions, and the centres of gravity of the areas found in this way. In addition to this, their areas should also be found, and the modulus of the section will easily follow.

It should be observed that, if the neutral axis has been correctly drawn through the centre of gravity of the original figure, and the construction of the modulus figure

(b)

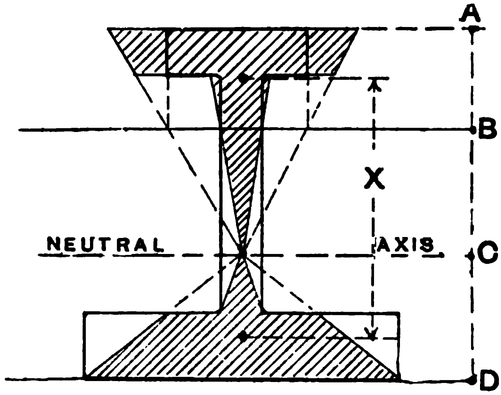


FIG. 14 (b).

has been accurately performed, the *area of that part of the modulus figure above the neutral axis will be equal to that below.* This will serve as a check on the correctness of the work. The most convenient way of ascertaining the areas is by means of an Amsler planimeter.

Let the area of that part of the modulus figure which is above the neutral axis be A_1; and that of the part below be A_2.

And let the distance of the centre of gravity of the first from the neutral axis be x_1, and that of the second x_2.

The modulus of the section will be

$$Z = A_1, x_1 + A_2 x_2.$$

But as

$$A_1 = A_2.$$

$$Z = A_1 (x_1 + x_2),$$

or if we call the distance, perpendicular to the axis, of one centroid from the other, X, then we shall have

$$Z = A_1 X.$$

It is usual to take inches and square inches as units, where the moments are expressed in "inch-tons" or "inch-pounds," and the stresses in tons or pounds per square inch.

14. Deflection of Beams.—In connection with testing it is necessary to have a knowledge of the relation of stress and strain, not only so far as the small portions of beam sections are concerned, but to know how to deal with loads as related to the strains they give rise to in the beam as a whole. Loads upon a beam cause it to assume a curved form, and the extent of departure, under stress, of a portion of the neutral axis of the beam from its originally straight position is termed the deflection. This is the strain which it is generally most convenient and easy to measure during a test, and it is necessary to know how this deflection is connected with the intrinsic properties of the beam, and with the loads upon it.

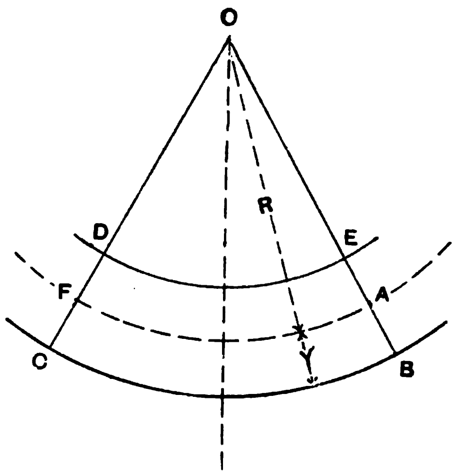


FIG. 15.

Let a portion of a beam be bent under stress. Two plane sections B E and C D, which were parallel before bending, are inclined after bending has taken place. If these sections are taken near to one another, and if C D and B E be continued, they will meet in a point O, which is the centre of curvature.

Let O A = R = the radius of curvature of the neutral surface. The neutral surface is under no stress, and is not altered in length.

Let C B be the length of an outside fibre, at a distance Y from the neutral surface.

Then, it will be easily seen that,

$$\frac{O\,B}{O\,A} = \frac{C\,B}{F\,A}, \qquad \text{or}$$

$$\frac{A\,B}{O\,A} = \frac{C\,B - F\,A}{F\,A}$$

But

$$\frac{C\,B - F\,A}{F\,A} = \frac{f}{E}$$

where f is the stress in the fibre and E the modulus of elasticity of the material of the beam,
and

$$\frac{A\,B}{O\,A} = \frac{Y}{R}$$

Therefore

$$\frac{Y}{R} = \frac{f}{E},$$

or

$$\frac{1}{R} = \frac{f}{E\,Y}.$$

But

$$\frac{f}{Y} = \frac{M}{I},$$

wherefore

$$\frac{1}{R} = \frac{M}{E\,I} \qquad . \quad . \quad . \quad \text{(XXV.)}$$

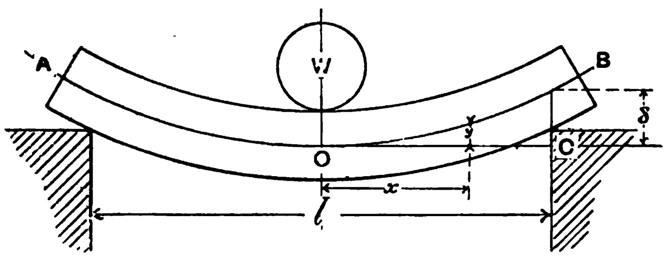


FIG. 16.

The beam, as a whole, is shown in Fig. 16. A horizontal tangent to the curved neutral surface A B is drawn at O; the deflection at the centre is C B or δ.

Now, from the properties of curves, it is known that

$$\frac{1}{R} = \frac{d^2 y}{d\,x^2}, \text{ very nearly.}$$

Therefore we may write

$$\frac{M}{EI} = \frac{d^2 y}{dx^2} \text{ or } EI\frac{d^2 y}{dx^2} = M$$

Take the simplest and most frequently occurring case in testing, where the beam is supported at the two ends and loaded in the centre with a load W. The reactions at the supports are $\frac{W}{2}$, and the bending moment of any section distant x from O is

$$M = \frac{W}{2}\left(\frac{l}{2} - x\right);$$

Integrating

$$EI\frac{d^2 y}{dx^2} = \frac{W}{2}\left(\frac{l}{2} - x\right),$$

we have

$$EI\frac{dy}{dx} = \frac{W}{4}\, l\, x - \frac{W}{4}x^2 + C,$$

C, being a constant of integration. When $x = 0$, the tangent is horizontal, so that $\frac{dy}{dx} = 0$, $C = 0$.

Therefore $$EI\frac{dy}{dx} = \frac{W}{4}\left(lx - x^2\right)$$

Integrating again

$$EIy = \frac{Wlx^2}{8} - \frac{Wx^3}{12} + c_2$$

c_2 being again a constant of integration. When

$$x = o, y = o, \text{ and } c_2 = o,$$

therefore we have

$$y = \frac{W}{EI}\left(\frac{lx^2}{8} - \frac{x^3}{12}\right)$$

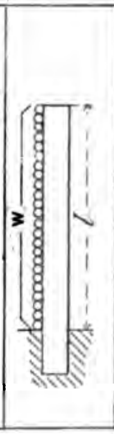
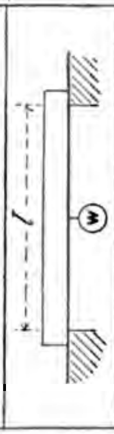
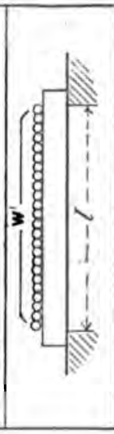
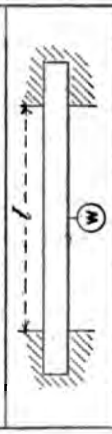
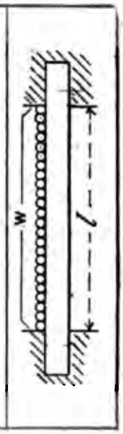
If we put $x = \frac{l}{2}$, y becomes the deflection at the centre, or

$$y = \delta = \frac{W}{EI}\left(\frac{l^3}{32} - \frac{l^3}{96}\right)$$
$$= \frac{Wl^3}{48\,EI} \quad . \quad . \quad . \quad . \quad . \text{(XXVI.)}$$

That is, for a horizontal beam of span l, and moment of inertia I, formed of a material whose modulus of elasticity is E, and loaded centrally with a weight W, the deflection at the centre, δ, is given by the above formula.

For beams supported in other ways and loaded differently, the general forms of the formulæ are the same, but the constant, 48, in the denominator gives place to others, according to circumstances.

TABLE I.—DEFLECTIONS.

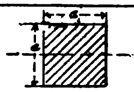
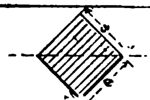
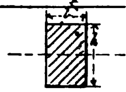
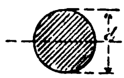
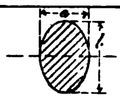
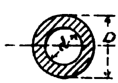
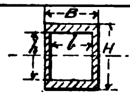
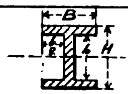
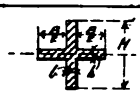
Conditions. Support.	Loading.		M	δ	E
Fixed at one end only.	At the outer end		$W.l$	$\frac{W\,l^3}{3\,E\,I}$	$\frac{W\,l^3}{3\,\delta\,I}$
Fixed at one end only.	Uniformly.		$W.\frac{l}{2}$	$\frac{W\,l^3}{8\,E\,I}$	$\frac{W\,l^3}{8\,\delta\,I}$
Supported at both ends.	In the middle.		$W.\frac{l}{4}$	$\frac{W\,l^3}{48\,E\,I}$	$\frac{W\,l^3}{48\,\delta\,I}$
Supported at both ends.	Uniformly.		$W.\frac{l}{8}$	$\frac{5}{384}\,\frac{W\,l^3}{E\,I}$	$\frac{5}{384}\,\frac{W\,l^3}{\delta\,I}$
Fixed at both ends.	In the middle.		$W.\frac{l}{8}$	$\frac{W\,l^3}{192\,E\,I}$	$\frac{W\,l^3}{192\,\delta\,I}$
Fixed at both ends.	Uniformly.		$W.\frac{l}{12}$	$\frac{W\,l^3}{384\,E\,I}$	$\frac{W\,l^3}{384\,\delta\,I}$

The above formulæ may be written

$$E = \frac{W l^3}{48 \delta I} \quad . \quad . \quad . \quad . \quad . \qquad \text{(XXVII.)}$$

Which is the form most useful in connection with experimental work; W, l, δ, and I can be measured, and from them E can be calculated.

TABLE II.—MOMENTS OF INERTIA.

Section.		Area.	Modulus of the Section.	Moment of Inertia.—I.
Square		a^2	$\frac{a^3}{6}$	$\frac{a^4}{12}$
Square		a^2	$\frac{a^3 \sqrt{2}}{12}$	$\frac{a^4}{12}$
Rectangle...		$b h$	$\frac{b h^2}{6}$	$\frac{b h^3}{12}$
Circle		$\frac{\pi d^2}{4}$	$\frac{\pi d^3}{32}$	$\frac{\pi d^4}{64}$
Ellipse.......		$\frac{\pi a b}{4}$	$\frac{\pi a b^2}{32}$	$\frac{\pi a b^3}{64}$
Hollow circle		$\frac{\pi}{4}(D^2 - d^2)$	$\frac{\pi}{32} \frac{(D^4 - d^4)}{D}$	$\frac{\pi}{64}(D^4 - d^4)$
Hollow rectangle.		$B H - b h$	$\frac{B H^3 - b h^3}{6 H}$	$\frac{B H^3 - b h^3}{12}$
I. Section...		$B H - b h$	$\frac{B H^3 - b h^3}{6 H}$	$\frac{B H^3 - b h^3}{12}$
Cruciform.		$b H + B h$	$\frac{b H^3 - B h^3}{6 H}$	$\frac{b H^3 - B h^3}{12}$

In the foregoing Table I. are the formulæ, which are most likely to be of use in testing work.

Here let W = the whole load on the beam.
„ l = the length of the beam.
„ E = the modulus of elasticity of the material.
„ δ = the deflection caused by the load W.
„ I = the moment of inertia of the section.
„ M = the maximum bending moment.

It should not be forgotten that the linear dimensions must all be taken in the same units, and the same remark applies to the forces.

Table II. contains the moduli and moments of inertia of the most commonly occurring beam sections will also be found useful for reference. More complicated sections should be treated graphically.

A most important thing to remember is that all the relations as to stress and strain which have just been described are only true so long as the beam is *perfectly elastic*. When the elastic limit has been passed these laws no longer hold.

15. Stresses and Strains in the Plastic State.—It has already been stated that if a strain following a stress is in any way permanent, then the material under consideration is in a more or less plastic state.

In the case of most of the metals stresses of a certain magnitude produce almost perfectly elastic strains; if these stresses are increased beyond a fixed point, a condition of semi-plasticity is reached, and the plastic condition becomes more pronounced as the stresses are further increased.

Thus if the loads upon a bar of mild steel be small, they will produce elastic extensions and the bar will return to its original length on the removal of the load; the extensions during this elastic stage are very small, and are only capable of being measured by means of delicate appliances. So long as the stress does not exceed about 15 tons per square inch the elastic condition will be maintained; but when the stress is increased to much beyond this point, the semi-plastic extensions begin, and what is called permanent set takes place. The point where elasticity ceases and plasticity begins is called the *elastic limit*. When this point is passed, the plasticity is only partial and some elasticity remains. As the load is increased, however, the plasticity becomes more and more perfect, and when the point of fracture is nearly reached, a state very nearly approaching to true plasticity is arrived at.

We have not at present sufficient knowledge of these plastic properties to enable us to deduce any very definite laws respecting them, but a few of the relations existing between stress and strain under plastic and semi-plastic conditions may be quoted here.

With the same notation as before (Fig. 4), let a bar be stretched to a length $(L+l)$ from an original length L; and let its original area of cross section be A, and the final cross sectional area a. Let us consider two stages: one at the beginning of the plastic state, and the other at or near the point of fracture. Assuming the volume to remain constant during the process and the cross section to remain the same along the whole length of the bar, we have

$$(\text{Initial volume}) = L \times A, \text{ and}$$

$$(\text{Final volume}) = (L+l)\,a.$$

But the volume being practically constant,

$$L \times A = (L+l)\,a$$

or,

$$\frac{L}{L+l} = \frac{a}{A}$$

or,

$$1 - \frac{L}{L+l} = 1 - \frac{a}{A}$$

This may be written $$\frac{l}{L+l} = \frac{A-a}{A} \quad \text{. . . (XXVIII.)}$$

or,

$$\frac{\text{Extension}}{\text{Stretched length}} = \frac{\text{Reduction of area}}{\text{Original area}}$$

The *percentage of reduction of area* is usually calculated for a bar after test, and is

$$\frac{\text{Reduction of area}}{\text{Original area}} \times 100;$$

and the *percentage of elongation* is usually reckoned as

$$\frac{\text{Extension}}{\text{Original length}} \times 100,$$

which is not the same as the ratio given above, where the extension is given on the *stretched* and not the *original* length.

So that from this we gather that so long as the bar remains parallel, and the volume is constant, the percentage of reduction of area, calculated on the original area, is always less than the percentage of elongation reckoned on the *original* length.

In compression, let

A = original area of the cross section;
A_1 = final area of the cross section;
L = original length of the specimen;
l = the shortening or strain.

Then

$$\text{Original volume} = \text{final volume}.$$

$$A \times L = A_1 (L - l)$$

$$1 - \frac{L}{L - l} = 1 - \frac{A_1}{A}$$

$$\frac{l}{L - l} = \frac{A_1 - A}{A} \quad . \quad . \quad . \quad \text{(XXIX.)}$$

or

$$\left.\begin{array}{c}\text{The percentage of}\\ \text{shortening reckoned on}\\ \textit{final}\text{ length.}\end{array}\right\} = \left\{\begin{array}{c}\text{The percentage of}\\ \text{increase of area, calculated}\\ \text{on the }\textit{original}\text{ area.}\end{array}\right.$$

16. Torsion.—When a shaft is subjected to a torsional or twisting moment, so long as the shaft remains perfectly elastic, we have seen (VIII.) that the twisting moment

$$T = \frac{\pi}{2} f r^3$$

where r is the external radius of the shaft. This is for solid shafts. Where they are hollow, we have

$$T = \frac{\pi}{2} f \frac{R^4 - r^4}{R}$$

As in the case of a prismatic bar under a tensile load, when the twisting moment exceeds a certain amount, the limit of elasticity is passed and, at first, the outer layers are strained beyond their elastic state, and this passing from the elastic to the semi-plastic state gradually proceeds from the outer surface inwards, until the whole cross section of the bar has passed beyond the elastic stage. When the elastic limit has been passed, the above equation is no longer applicable, and the intensity of the stress, which, under the elastic conditions, was proportional to the distance from the axis of the shaft, becomes more nearly distributed over the whole area. Experiments show that after the elastic limit has been passed, the shaft begins to assume a condition of partial plasticity, which, as the twisting proceeds, approaches the state of perfect plasticity, but never actually reaches it.

The above are the relations between stress and strain under the elastic conditions.

At the other limit—perfect plasticity—we have the shearing stress uniform over the whole area of the cross section.

Thus, $f = \text{constant}$.

The resistance of each elemental ring of the section is

$$f\,2\,\pi\,x\,\delta\,x$$

and its moment $f\,2\,\pi\,x^2\,\delta\,x$.

So that the total resistance,

$$\mathrm{T} = 2\,\pi f \int_0^r x^2\,d\,x$$

$$= \frac{2}{3} f\,\pi\,r^3 \quad . \quad . \quad . \quad . \quad . \quad \text{(XXX.)}$$

$$= \frac{1}{12} f\,\pi\,d^3$$

For hollow shafts

$$\mathrm{T} = \frac{2}{3} f\,\pi\,(\mathrm{R}^3 - r^3) \quad . \quad . \quad . \quad \text{(XXXI.)}$$

$$= \frac{1}{12} f\,\pi\,(\mathrm{D}^3 - d^3)$$

17. The Flow of Metals.—It would seem strange at first sight to talk about flow taking place in a substance whose normal condition is that of a solid. But a little thought will no doubt bring to mind familiar instances of phenomena in solid bodies which are in themselves very similar to many of those which are found to manifest themselves in the more palpably fluid substances. We can proceed by easy stages from the flow of liquids to the flow of solids. Thus we are quite familiar with the flow of water, the more viscous flow of oils, and the still more viscous flow of wet clay and mud. When a wax candle is placed in an unsupported horizontal or inclined position, it will be observed that after a time it will be found to have assumed a curved shape, and if the conditions are favourable may ultimately collapse altogether. This is undoubtedly a case of a movement of the particles, or flow, taking place in a substance which we usually look upon as solid. A similar case is that of a rod of sealing wax left for a time under precisely similar conditions. It will be found that the weight of the wax—generally looked upon as a brittle substance when cold—has been sufficient to

cause a downward curvature of the rod. If a ball of hard and brittle tar be left standing for a time the spherical shape will gradually disappear, and the tar will settle down until it becomes a circular disc.

A substance which exhibits the phenomena of flow to a striking degree is ice. Under sufficient pressure, this otherwise solid and even brittle substance can be made to flow out of an orifice much in the same way as a viscous fluid.

A still more striking instance of this molecular movement was quoted some years ago by Professor Blake, of Connecticut, U.S.A., who drew attention to certain geological phenomena which he had had under observation. What he noticed was that in certain conglomerates, the pebbles were all found to be of an elongated, flattened, ellipsoidal form. He was forced to believe, from other evidence which he held to be conclusive, that these shapes were entirely due to an elongation and compression having taken place under very great force. After admitting that in all the cases quoted, a movement of the particles or molecules must have taken place, what is called the flow of metals is not very difficult to recognise.

In the first place, we are quite familiar with the fact that under conditions of high temperature, when wrought iron and steel are at a red heat, they assume a very visibly plastic condition, and can be hammered, pressed, or rolled into all manner of shapes. To effect these changes of shape and dimensions, certain stresses need to be applied or flow will not take place, at any rate in the short space of time required, unless these stresses exceed a certain minimum value.

If the metal be treated in a similar manner when in the cold condition, similar effects may be produced, with certain modifications, but the applied stresses must be much greater before any flow will take place. Under this heading we have the cold stamping of iron and steel, wire drawing, the cold drawing of pipes, in all of which there is a most decided flow of the metal taking place, from one part of the mass to another. With the softer metals, such as lead, the appearance of fluidity is even more noticeable, and very frequent use is made of this property in the manufacture of lead for commercial purposes. For instance, pipes of lead are made by forcing the metal under very high pressure through annular dies, the metal flowing out easily and smoothly, and retaining the form given to it.

Thus, it will be seen that there are a number of solid bodies which, under certain conditions, can be made to exhibit properties in many ways similar to those of the more viscous fluids. Of these solid bodies some are deformed and made to flow under exceedingly small stresses, often less than those induced by their own weights, if these stresses are only allowed to act for a sufficiently long time; others require greater stress to bring about the plastic phenomena; while there are some which require the application of very great stresses indeed before any signs of semi-plasticity show themselves.

18. Fluidity.—When the stress upon a substance exceeds a certain limiting value, the distortion or strain will take place indefinitely without any further increase of stress. This is seen in the case of a bar of a ductile material when the breaking tensile load is nearly reached. When the bar becomes plastic, a condition of unstable equilibrium is reached, and a rapid extension takes place and a simultaneously rapid contraction of area. As the area decreases the intensity of stress on the bar increases, with the result that fracture very soon takes place, being generally preceded by local contraction.

This limiting value of the stress, when plasticity is reached, has been called by M. Tresca "the pressure of fluidity."

With the same notation as before, if p is the pressure of fluidity the load on a tension bar, when plasticity is reached, is

$$W_1 = p\,A \quad . \quad . \quad . \quad . \quad \text{(XXXII.)}$$

A being the area when fluidity begins. At a later stage, when the area has been reduced to a, the load upon the bar will be

$$W_2 = p\,a \quad . \quad . \quad . \quad \text{(XXXIII.)}$$

and as

$$\frac{A}{a} = \frac{L + l}{L}$$

we have

$$\frac{W_1}{W_2} = \frac{L + l}{L}.$$

TABLE III.—USEFUL FORMULÆ.

The following are the formulæ whose use is most frequently required when working out the results of testing operations, and, in addition to those already tabulated, will be found useful for reference.

The symbols used have the following meanings:—

D = the outer diameter of a hollow cylindrical shaft in inches.
E = the modulus of elasticity in tension per square inch.
G = the modulus of rigidity in shearing and torsion in pounds per square inch.
I = the moment of inertia of a beam section.
K = the modulus of elasticity of volume in pounds per square inch.
M = the bending moment on a beam, in inch-pounds.
T = the twisting moment on a shaft in torsion, in inch-pounds.
W = the central load on a horizontal beam, in pounds.
Z = the *modulus* of the section of a beam.
b = the breadth of a beam in inches.
d = the internal diameter of a hollow, or the external diameter of a solid, shaft in inches; also used to denote the depth of a beam in inches.
f = the maximum stress on a beam section, or on the section of a cylindrical shaft, in pounds per square inch.
l = the length of a beam or shaft in inches.
m = Poisson's ratio.
r = the radius of a solid shaft in inches.
δ = the central deflection of a beam in inches.
ϕ = the angle of twist of a cylindrical shaft in radians.
a = angle of twist in degrees.
π = the ratio of the circumference of a circle to its diameter = 3·1416.

ELASTICITY.

$$\frac{G}{E} = \frac{1}{2\left(1 + \frac{1}{m}\right)}$$

In the metals $m = 4$, so that in this case

$$\frac{G}{E} = \frac{2}{5}$$

Also, $$m = \frac{6\,K + 2\,G}{3\,K - 2\,G}$$

CROSS-BREAKING, BEAMS.

$$M = f\frac{b\,d^2}{6} = f\,Z$$

and, $$E = \frac{W\,l^3}{48\,\delta\,I}$$ for a central concentrated load.

TORSION.

Where the shaft is elastic,

$$T = \frac{\pi}{16} f d^3$$

$$T = \frac{\pi}{16} f \frac{D^4 - d^4}{D}$$

$$T = \frac{\pi}{2} \frac{\phi G r^4}{l} = \frac{\pi^2 a G r^4}{360 \, l}$$

$$G = \frac{32}{\pi} \frac{l T}{\phi d^4} = \frac{5760 \, l T}{\pi^2 a d^4}$$

$$G = \frac{32}{\pi} \frac{l T}{\phi} \left(\frac{1}{D^4 - d^4} \right) = \frac{5760 \, l T}{\pi^2 a} \frac{1}{(D^4 - d^4)}$$

Where the shaft is plastic,

$$T = \frac{1}{12} f \pi d^3$$

and

$$T = \frac{1}{12} f \pi \left(D^3 - d^3 \right)$$

Chapter II.

TESTING MACHINES.

19. Every material of engineering whose strength is of any importance has, at some time or another, to resist force. The general intention, in all kinds of testing, is to so deal with small specimens of the material in question that they may be subjected to stresses similar to those which they will be expected to withstand when forming parts of actual structures.

The stresses imposed on parts of structures are, or should be, safe stresses—that is to say, stresses which do not in any way produce deformation or deterioration of the material. In the testing machine, however, the treatment is as a rule different. In commercial testing, at all events, most specimens are tested to destruction, that is to say, stresses of such magnitude are applied that complete failure of the material takes place. This failure may take the forms of rupture, crushing, splitting, or crumbling, according to the nature of the material and the kind of stress imposed. In some tests, especially in connection with educational and research work, the forces applied are only such as will cause elastic deformations, in which case they may be repeated as often as may be desired.

The reason why specimens of materials are tested to destruction is that only by doing this can those qualities of the material be made to show themselves, which will enable the observer to gain a sufficient knowledge of the really important strength properties of his material. It is not sufficient to know, for instance, what is the maximum safe load that may be applied to a wrought-iron tension bar without producing permanent deformation, but more important than this is a complete knowledge of the uniformity, the ductility, and the nature of the internal structure of the iron; and such information as this can only be obtained by actually breaking the bar or testing it to destruction.

When a specimen is to be tested, three functions have to be performed by the appliances used. These are as follow:—

(*a*) The specimens must be firmly held, and such loads as may be desired applied. These must be steady loads

and constant in their application, whether the specimen is deformed or not.

(*b*) The magnitude of the applied load must be capable of measurement to a reasonable degree of accuracy.

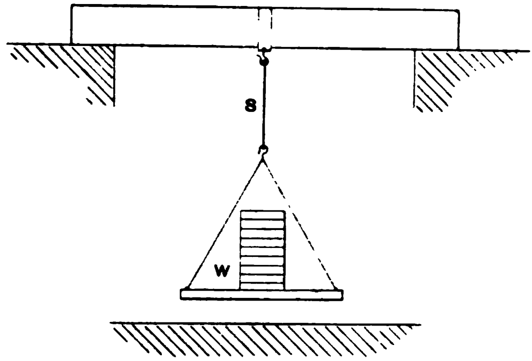


FIG. 17.

(*c*) The magnitude or extent of the deformations produced by the loads must also be capable of being measured.

Of these three conditions the two first are necessary in all cases, and the appliances for carrying them out form the main features of all testing machines. The last condition is not indispensable, and is generally fulfilled by some piece of apparatus apart from the testing machine itself. It is with the two first that we are at present concerned, and the manner of carrying them into effect, which is employed in all the chief types of testing machines, will next be described.

20. Simple Forms.—The simplest kind of test that can be applied to almost any material is that under a tensile load, and as tensile tests form the greater proportion of testing work, most testing machines are arranged, in the first instance, for this kind of test, and usually slight modifications in the arrangement of the machine are added to enable tests of other kinds to be made.

We have seen that it is necessary in a tension test to be able to apply such loads as may be desired, and at the same time to be in a position to accurately measure these loads as they are applied. It will be fairly obvious that the simplest way of thus applying loads to a specimen, and at the same time measuring them, is by fixing the specimen to be tested in a vertical position, with the upper

end firmly attached to a rigid support, and applying the loads in the form of deadweights to the lower end. This is shown in the accompanying Fig. 17, where a wire, S, is being tested by placing weights in a scale pan attached to its lower end, while its upper end is fastened to a hook in a massive beam, resting at its ends upon supports. This is at once a simple and inexpensive form of testing machine, but it is an arrangement which can only be used to a very limited extent.

So long as the cross section of the specimen is small, or the material of such a nature as is unable to resist great tensile stress, a "deadweight" arrangement of this kind may be used. But when larger specimens of stronger materials have to be tested, other means must be sought for, both for applying the loads and for measuring them. When the loads are movable weights of a few pounds they are easily lifted on and off the scale pan, but when hundredweights and tons come to take the place of pounds, it is no longer possible to deal with these in the same way.

21. Tensile Testing Machines.—In the deadweight machine the application and measurement of the load are effected by one and the same operation; in the larger testing machines, which we are now about to consider, these two are not quite the same thing. The principle in all tensile testing machines is the same. The specimen to be tested is firmly gripped or held at its two extremities. The shackles in which these ends are held are attached respectively to a measuring appliance at the one end, and at the other to a part of the machine which is so arranged as to be capable of exerting the required pull upon the specimen, and not only to exert a statical pull, but to exert this pull steadily through such a distance as shall be determined by the stretching of the bar, in order that the end at which the magnitude of the load is measured shall not alter its position relatively to the measuring apparatus.

22. Methods of Applying the Load.—It is perhaps necessary to state a little more definitely what is meant by "applying the load." The application of the load is in reality the controlling or regulation of the load at the will of the operator. When a bar is being subjected to a tensile load there must necessarily be at the respective ends two equal and opposite forces, and provision must be made for the application of these two. If one end is firmly held, and the load applied at the other, an equal and opposite

pull must come on the fixed end in order to prevent its being pulled away. So that the same load is really being *applied* to both ends simultaneously. It is, however, customary to speak of the straining apparatus being applied to the movable end, and the measuring appliance at the stationary end, although in reality both are exerting the same pull. In some few cases the measurement of the load and the straining are effected at the same end of the specimen.

The two methods most in vogue for applying the load are those of hydraulic power and screw gearing. In all the larger testing machines used in this country the former is almost universally employed on account of its great capability of being easily controlled and manipulated, and by reason of its greater efficiency as compared with screw gearing.

In many of the smaller machines, and also in one or two of the larger machines used in America, screw gearing is employed. By means of a direct-acting screw, or a worm wheel rotated by a worm and acting as the nut on a fixed screw, bars of small dimensions can be readily strained and broken by the application of manual power, although the mechanical efficiency of such arrangements is extremely low, in some cases as much as 90 per cent or more of the work done by the operator being lost in overcoming frictional resistances. With a conveniently quick movement of the straining shackle the limit of load which can be applied by manual power is probably from two to three tons. Beyond loads in this neighbourhood manual power must be abandoned, and steam or other mechanical power made use of.

23. Measurement of the Load.—The magnitude of the load is, in almost all cases, measured by some kind of lever weighing machine. In this way small movable weights, applied at great leverage, which may be variable or constant, may be used to measure loads very many times their own magnitude. It is according to the manner in which these weighing appliances are arranged and used that the various testing machines are divided into several distinct classes. They may be placed as follow:—

I. SINGLE-LEVER MACHINES.—(*a*) High power, with constant leverage, and movable small weights. (*b*) Low power, with variable leverage and constant large weight.

II. MULTIPLE-LEVER MACHINES.—(*a*) High power, with three or more levers, with variable moving weights on

the last lever. (*b*) Low power, with two or three levers, and variable moving weights on the last lever.

III. MANOMETER, OR FLUID PRESSURE MACHINES.—It will now be convenient to briefly describe these various types, and to limit the detailed description to the more familiar machines only, and to those with which readers may be likely to come in contact.

I. SINGLE-LEVER MACHINES.—On Fig. 18 are shown, at (*a*) and (*b*), diagrammatic views of two representative machines of this type. That at (*a*) is the Werder machine, largely used for scientific work on the Continent. In this

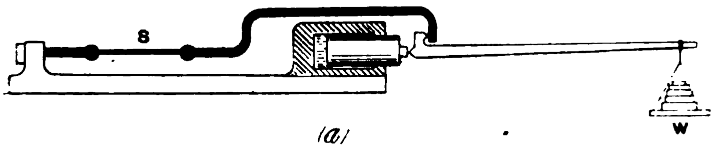


FIG. 18*a*.

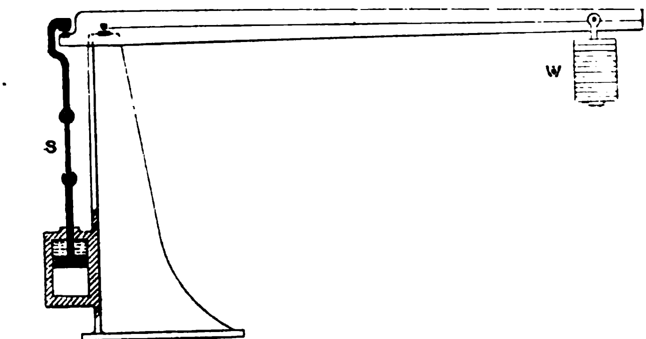


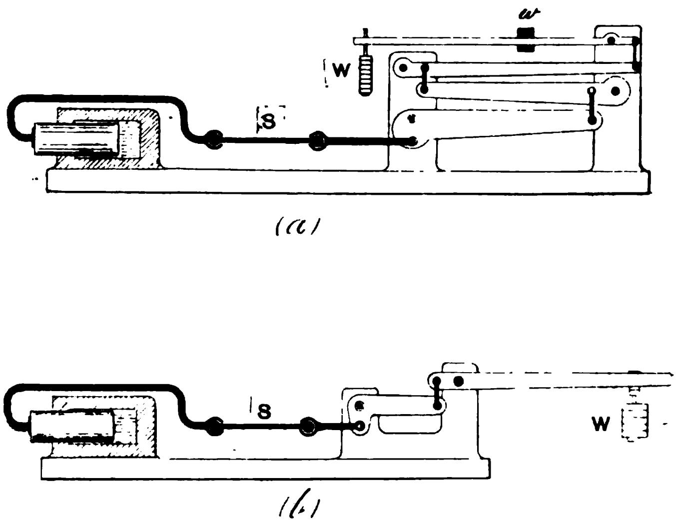
FIG. 18*b*.

machine there is a single bell-crank lever; the ratio of the length of the long arm to that of the short one is extremely large, so that very small weights placed on the scale pan, at the outer end of the large arm, produce correspondingly great levers on the specimen at S. It will be noticed that in this machine, on account of the lever being a right-angled one, the pull on the specimen is horizontal.

The machine shown at (*b*) has a straight arm and comparatively low leverage, so that the weight or weights W must be large. In some machines of this type the weight W is invariable in magnitude and acts as in a steelyard, the pull on the specimen depending upon the position of W

with respect to the fulcrum; in others, generally the smaller kinds, W is variable, the fine adjustments being obtained by the movement of a small constant weight on the lever.

The chief example of this type of machine is to be found in the Wicksteed single-lever machine, in which a large moving weight is used. A number of smaller machines of the same kind are constructed by various makers. These machines are all vertical machines, the specimens to be tested being held in an upright position.



FIGS. 19.

II. MULTIPLE-LEVER MACHINES.—Of the second type of testing machines two examples are shown in the accompanying sketch, Figs. 19. The diagram (*a*) represents the multiple-lever machine designed by the late Mr. Daniel Adamson. In this machine there are four levers, the first a bell-crank lever, and the remaining three straight ones. The total leverage is 15,000 to 1, so that a very small moving weight on the last lever measures a pull in the specimen fifteen thousand times as great. (*b*) is the two-lever machine of Messrs. Greenwood, of Batley. Here the leverage is 100 to 1, and the load upon the specimen is controlled by the application of the variable and movable

load W to the second lever. The first lever is bell-cranked, and therefore the position of the specimen is horizontal.

III. The accompanying sketch, Fig. 20, is intended to represent the principle upon which machines work which utilise fluid pressure for the measurement of the load. The best example of this type of machine is the Emery

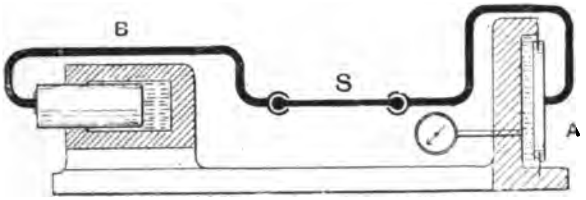


FIG. 20.

machine, whose use is almost entirely confined to America. This machine is said to possess extraordinary sensitiveness, and to be very easy to use and manipulate.

In the diagram the straining cylinder is at B, S is the specimen, whose right-hand end is attached to a diaphragm or flexible piston in what is virtually a shallow cylinder of large diameter at A. The total pressure upon this diaphragm is transmitted as the load to the specimen; and the magnitude of this pressure, and therefore of the load, is measured by conveying the fluid to a smaller diaphragm, which again acts upon a system of measuring levers and balance weights. This is a horizontal machine.

In all the machines which have been mentioned, the load is applied and the stretch of the specimen taken up by means of an hydraulic ram. The weighing appliances and the hydraulic ram are at opposite ends of the specimen in the case of the Wicksteed, Greenwood, Adamson, and Emery machines. The Werder machine alone of those which have been mentioned has both at the same end of the specimen, the other end being rigidly fixed to an abutment attached to the bed of the machine.

Before proceeding to compare these various machines and to discuss their respective advantages and disadvantages it will be well to describe them in detail.

*THE WERDER TESTING MACHINE.

24. The Werder machine has been described as the one in which tests have been made, excelling in precision and

*Unwin's "Testing of Materials," p. 128

accuracy those of every other type of machine. Its general arrangement is shown on Fig. 18. The left-hand end of the specimen S is held firmly in grips attached to the rigid frame of the machine, and incapable of movement in either direction. The other end is held by grips, which are attached through links to the knife edge at the end of the small arm of the bell-crank lever. The other knife edge bears on the fulcrum, which is carried upon the outer end of a horizontal ram, working under hydraulic pressure in a cylinder rigidly fixed to the framing of the machine.

In the Werder machine used by Bauschinger, capable of exerting a pull on a specimen of 100 tons, the fulcrum distance, or the distance between the two knife edges on the short arm of the lever, is only 4 millimetres (equivalent to about $\frac{3}{16}$ in.); and as the long or horizontal arm of the lever is 2,000 millimetres, or 500 times the length of the small arm, a leverage of 500 : 1 is obtained.

The load on the specimen is controlled by adding weights to a scale pan hung from a knife edge at the outer end of the lever. In order that the full load of 100 tons may be applied, it is only necessary, with this large leverage, to have a load in the scale pan of

$$\frac{2{,}240 \times 100}{500} = 448 \text{ lb.}$$

or, 4 cwt.

As the load upon the specimen is increased by the placing of small weights in the scale pan, and as the specimen in consequence stretches, the lever relinquishes its horizontal position, and becomes inclined downwards. To counteract this and keep the lever floating horizontally, water is pumped into the ram cylinder by means of hand pumps, the ram driven outwards, and the lever restored to its proper position. In order to ascertain when the lever is floating horizontally, a spirit level is attached.

In addition to its use for tensile testing, special attachments can be made for the purposes of compression, bending, and torsion.

THE BUCKTON-WICKSTEED SINGLE-LEVER TESTING MACHINE.

25. This, the second of the single-lever machines, has already been shown diagrammatically in Fig. 18, and its general principle briefly explained. The simplicity of this principle makes the machine very convenient to use and easy

to manipulate. The lever is a straight horizontal one resting upon a horizontal knife edge; the upper end of the specimen to be tested is attached to the short arm of the lever; a heavy poise or balance weight rests upon the long arm, and causes the short end to exert a pull upon the specimen. The weight is a heavy one, and of invariable magnitude, and the variations in the load upon the specimen depend upon the relative positions of the poise weights.

The lever being straight, and the force exerted by the balance weight being vertically downwards, the pull upon the specimen is vertically upwards, and consequently the specimen must be held in a vertical position. It may be mentioned that most of the large machines of the Buckton or Wicksteed type, which are in use at the present time in this country, are either of a 50-ton or 100-ton capacity.

[*]**26. The 50-ton Machine.**—On Fig. 21 is shown a side elevation of a Buckton 50-ton testing machine, and a careful inspection of this figure ought to make clear to the reader its general principle and arrangement, and the way in which it is manipulated. Most of the Buckton-Wicksteed vertical machines in use in testing laboratories in this country and abroad are designed and built upon the same lines, although many of them have their own peculiarities in detail; these will be referred to later.

The distinctive features of the Buckton-Wicksteed type of machine have already been briefly referred to and described. The tension specimen which is to be tested is held at its lower extremities by wedge clips resting in a shackle, which is linked to the piston rod of an hydraulic cylinder; this is bolted to the lower part of the main standard of the machine.

The upper end of the specimen is fixed in a similar way to a shackle hanging from a suspending link, which is itself hung from the knife edge D. This knife edge is fixed into the beam or steelyard A; so that any pull that is put upon the specimen is directly transmitted to this knife edge in the beam. The beam itself consists of two plates or sides joined by cross pieces at the ends and at intermediate points, and is, for the most part open between the plates. In some machines this beam is constructed of steel side plates and cast-iron cross pieces; in some others the whole is made in one casting.

The steelyard has fixed into it a knife edge B, the edge

[*] Proc. Inst. Mech. Eng., 1882 and 1886.

pointing downward, and this rests upon a hardened steel plate attached to the top of the standard, which in this way carries the load on the specimen as well as the whole

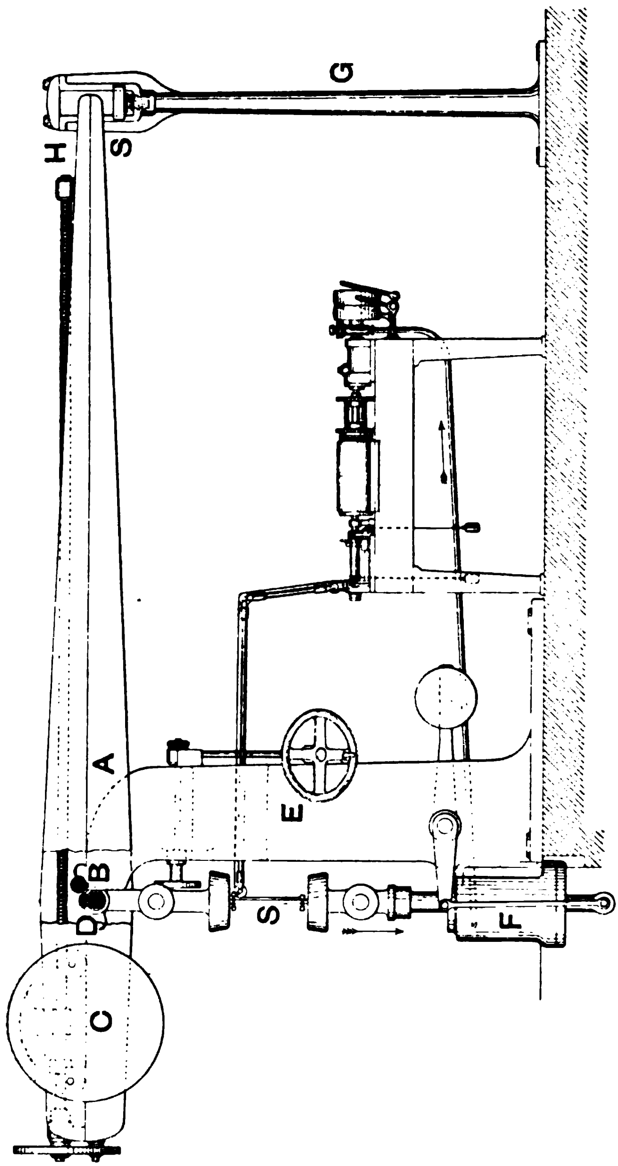


*Fig. 21.

* Proc. Inst. Mech. Eng., 1882.

weight of beam, poise weight, and fittings. The two knife edges, one of which (D) points upwards, and the other (B) downwards, are so placed that when the beam is in its normal position these two edges lie in a horizontal plane, which also should contain the centre of gravity of the beam and poise weight.

The poise weight, marked C in the figure, weighs 1 ton, and consists of two solid cast-iron discs joined by a connecting piece at the top, and it hangs, saddle fashion, over the beam. It rests on the beam through four small wheels or rollers, which traverse pathways on each side of the beam. In this way the weight can be moved from end to end of the beam. Its movement and position is controlled by a screw running the whole length of the beam, and rotated by gearing. The traversing of the weight can be effected by the movement of a hand wheel, but in many instances a belt connection is made, so that the weight can be traversed by power by the simple movement of a lever. This is especially useful for rapid testing, and is almost indispensable for bringing the weight back to its zero position when a test has been completed.

When there is no pull on the specimen, and the beam is perfectly balanced, the poise weight C is in the position shown, to the left of the knife edges. It has been said that the knife edges and the centre of gravity of the beam lie in a horizontal plane. This position of the centre of gravity can be adjusted by means of a small balance weight, which is capable of being raised or lowered; by bringing the centre of gravity into the same horizontal plane as the knife edges a condition of neutral equilibrium is obtained, which is necessary for accurate testing. The plan of having the poise weight at the negative end of the steelyard, when the machine is in equilibrium, is quite a distinctive feature of the Buckton single-lever machine. In order to increase or measure the load upon a specimen held in the clips it is only necessary to rotate the hand wheel E either by hand or power, and so cause the poise weight C to move upon its rollers towards the right-hand end of the lever. This throws the whole system out of balance, and causes a load to come upon the specimen. As the poise weight is 1 ton, and the distance between the knife edge B and the knife edge D, 3 in., for every 3 in. traversed by the weight in moving along the beam in the direction of the long end, an additional load of 1 ton is put upon the specimen in the jaws. The extent

of this movement from the normal position shown in the figure, to the extreme position of the right-hand end of the beam, is

$$50 \times 3 = 150 \text{ in.},$$

which is equivalent to a maximum pull upon the specimen of 50 tons.

The pull on the specimen being 50 tons, and the poise weight 1 ton, when the full load is on the specimen the effect is the same as would be produced by a simple lever whose length of the arms were 150 in. and 3 in. But, when the poise is at the negative end of the lever, it is balancing the heavy end, which is itself equivalent to 1 ton hung at the end of the otherwise balanced lever. So that when the poise has moved to its full extent, the actual weight used for measuring the stress is really double that of the poise, or 2 tons, and the actual leverage is

$$\frac{50}{2}, \text{ or } 25 \text{ to } 1$$

It will be seen that any variation of the magnitude of the load upon the specimen depends upon only the position of the poise-weight, which itself is invariable. In order, therefore, that the operator may be able to ascertain and observe the load, a steel graduated scale is attached to the side of the beam, by means of which the position of the weight, and therefore the magnitude of the load, may be gauged. The scale of the machine in question is divided into equal lengths of 3 in., each equivalent to 1 ton; each of these tons is subdivided into tenths and twentieths; and by means of a sliding vernier attached to the moving weight further subdivisions into hundredths and two-hundredths of a ton may be effected. In all machines of this type the position of the vernier is made adjustable, so that when the poise weight has been brought to such a position that the beam is in perfect equilibrium, previous to a test, the vernier can be set with its zero point coinciding with the zero of the main or parent scale. This adjustment is often rendered necessary in the case of some tests, such as those in compression and bending, when extra heavy tackle has to be hung from the shackles and the beam is thrown out of balance; this state of things also exists when very heavy specimens are being tested.

In order that the position of the weight may be truly indicative of the load upon the specimen the beam must

at all times be floating—that is to say, it must be acted upon by no other forces than its own collective weight, the pull on the specimen, and the pressure upon its main knife edge. It will be noticed that at the right-hand end of the beam in the illustration there is a pillar G, terminating at its upper end in two stops H and S. The beam is free to oscillate between these limits, but cannot pass beyond them. When the beam is horizontal and in equilibrium, its end is about midway between these stops, and it should remain as nearly as possible in this position throughout a test. If the beam is resting upon the bottom stop, some of the weight of the beam and poise is being taken up by it, and the position of the weight is no indication of the load on the specimen. On the other hand, should the end of the lever rest against the upper stop, the load on the specimen will be greater than would appear to be the case from the scale reading, because there is an additional and unknown force acting upon the beam through the stop, and at the full leverage of the machine.

It is, therefore, extremely important that the beam be always kept floating freely between the upper and lower stops. To maintain this condition, use is made of the hydraulic appliances. At F is a vertical hydraulic cylinder bolted to the lower end of the standard of the machine. In this cylinder works a piston fitted on the upper side with a cup leather. A piston rod passes through the top of the cylinder, and is made watertight by a second cup leather. The upper end of this rod screws into the crosshead which carries the lower holding shackle. In the earlier machines, two cup leathers were fitted to the piston, and water under pressure could be admitted either above or below the piston—above, when it was desired to increase the load on the specimen, and below, when the piston had to be brought back to its normal position after the completion of a test. In the later designs the piston is brought back to its normal position by means of a balance weight acting at the end of a small lever; this is shown in the figure.

Suppose a bar, S, to be in the machine, and the load to be moved along the beam. If the beam is perfectly horizontal to begin with, the stretching of the specimen, which necessarily accompanies an increase of load, will cause it to fall towards the lower stop, very slightly at first, while the specimen is still elastic, and more rapidly at a later stage, when permanent set begins to take place. It, therefore, becomes necessary to bring the beam back to its horizontal

position, and to, as nearly as possible, keep it there. To raise the right-hand end of the beam the lower end of the specimen must be moved in a downward direction, and this is effected by slightly opening the hydraulic valve which admits the high-pressure water above the piston. The piston is thus moved downwards, it carries with it the lower end of the specimen, and the beam is raised to its normal position.

During a tensile test, therefore, especially if the material tested be of a ductile nature, the machine has to perform two distinct functions—namely, that of applying and measuring the loads, and, at the same time, taking up the stretch of the specimen in such a way that the end of the specimen at which the load-weighing apparatus is attached does not, to any appreciable extent, alter its position with respect to the body of the machine.

These two functions are under the control of the operator who is performing the test. He regulates the loads either by means of the hand wheel rotating the screw, or by means of a belt lever which causes the same thing to be done by power; and he takes up the stretch or strain by allowing or causing water under pressure to flow into the straining cylinder.

It will be noticed that on Fig. 21 is a small piece of apparatus to the right of the standard of the machine. This is Mr. Wicksteed's appliance used for the production of autographic diagrams, and will be described later.

Fig. 22 shows a general perspective view of the same machine as that represented on Fig. 21.

27. Methods of Applying the Hydraulic Power.—In the Buckton-Wicksteed machines now in use, there are, so far as the author is aware, three different ways in which the water under pressure is supplied to the straining cylinder. These are, first, by means of a set of power-driven pumps working with an accumulator; secondly, by means of an intensifier; and lastly, by what is called a quiet compressor. These will be briefly described.

28. Pumps and Accumulators.—In this arrangement water is drawn from a supply tank, and pumped at a high pressure into the ram cylinder of an ordinary hydraulic accumulator, which is so loaded as to maintain the required pressure. From the accumulator the water is delivered to the ram cylinder of the machine, and the supply regulated by means of a valve manipulated by the operator. When a test has been completed, an exhaust valve is opened and

the water released and allowed to flow back to the supply tank. The pumps are usually driven by power transmitted by belts from the line shafting, though in some cases the pumping can be, and is, effected by manual labour. In

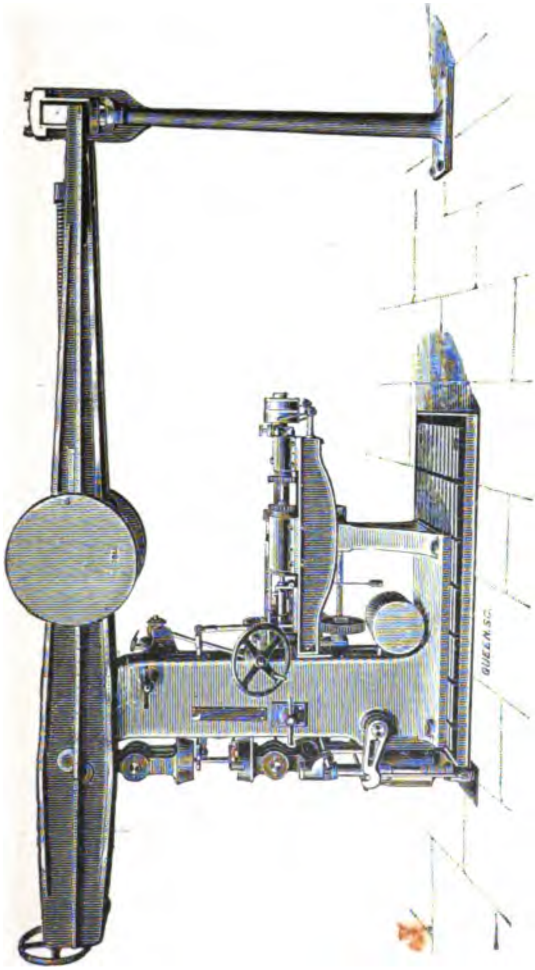


FIG. 22.

the case of belt-driven pumps, the belt fork is provided with a tappet rod, so arranged that when the accumulator load reaches the top of its stroke, it engages with one of the tappets and thus throws the belt on to the loose pulley,

and the pumping ceases. The second tappet performs the converse operation of starting the pumps when the load falls below a certain point.

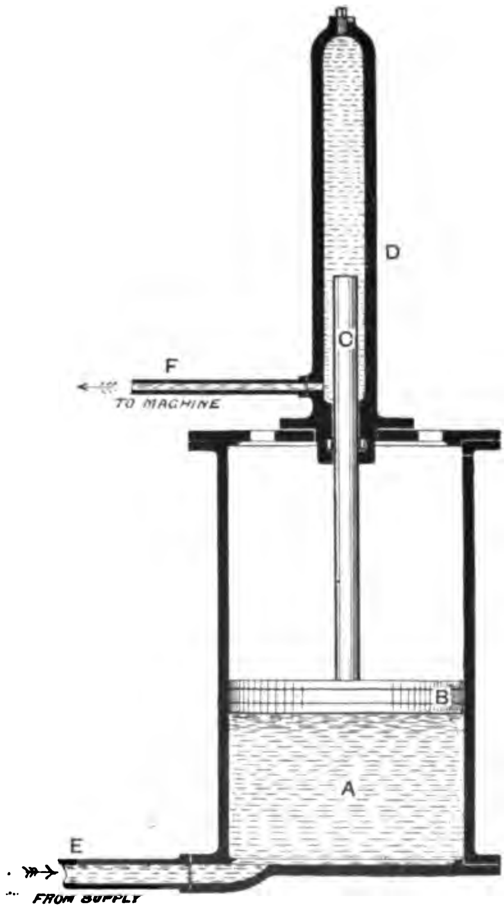


FIG. 23.—Hydraulic Intensifier.

29. Intensifier.—This mode of providing a supply of high-pressure water may be used when there is no mechanical power available, and at the same time there is an abundant supply of water at a comparatively low pressure. The general arrangement of the intensifier is shown in the accompanying diagram, Fig. 23. A is a cylinder of large diameter, say 2 ft. 6 in., in which a piston, B, works. The

rod C of this piston performs the function of a ram working through a stuffing box in the smaller ram cylinder D. If the ram or piston rod is, say, 3 in. in diameter, the respective areas of the piston and ram are in the proportion of 100 to 1; and, neglecting friction, the water pressures will be in the inverse ratio. Thus, if water at 50 lb. per sq. in. pressure be supplied at E to the under surface of the piston, it will force water from the outlet pipe of the upper cylinder at a pressure of

$$50 \times 100 = 5{,}000 \text{ lb. per sq. in.}$$

The supply of water to the straining cylinder of the machine can either be directly controlled by a valve in the supply pipe F, or it can be regulated by controlling the supply of low-pressure water to A through E. The latter is the better way.

30. The "Quiet" or Screw Compressor.—Here the water is supplied at high pressure by a ram being forced into a ram cylinder by means of screws and gearing worked by belts from the line shafting. Its mode of action is shown in Fig. 24. A countershaft on the compressor is rotated by means of a belt from an overhead line shaft. This

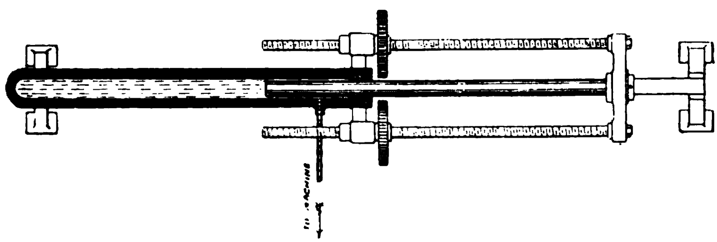


FIG. 24.—Quiet or Screw Compressor.

countershaft drives, through intermediate gearing, two spur wheels, acting as nuts upon the pair of screws, which are in this way drawn in the direction of their length along the two sides of the ram cylinder. The ram itself is carried by a crosshead, which is attached to the ends of the screws, so that a movement of the screws means also a movement of the ram. As the ram enters the cylinder it drives out a supply of water at the required pressure.

When working the machine, the movement of the ram in the straining cylinder is brought about by the movement of a hand lever, which shifts the belt on the compressor

from the loose to the fast pulley, and so puts the compressing ram in action. Two belts are used with a quick return motion, so that the compressing ram can be run out more quickly than it is driven in.

The adoption of one or another of these three systems of hydraulic supply depends, to some extent, upon the existing conveniences of the testing laboratory—whether there is shaft power available, whether there is an abundant supply of low-pressure water, and so forth. Probably the three systems might be placed in the following order, as regards their convenience and adaptability: (1) Pumps and accumulator; (2) Intensifier; (3) Screw compressor. In much of the testing work carried out, speed and continuity of action are of the greatest importance. This latter is lacking in both intensifier and compressor, whose immediate capacity is limited to the volume swept out by one stroke of the ram. Nothing is more annoying than to have to wait, either at the beginning of a test or, what is worse, in the middle of one, until the ram has been brought back to its initial position ready for another stroke. This is a thing that may happen, especially when the specimen is a long one of very ductile material, requiring a large movement of the straining ram before fracture takes place, and also when the cup leathers are a little leaky.

On the other hand pumps can be kept continuously running, and any excess of water coming from them simply goes to the accumulator to wait until its use is required. An objection sometimes raised against pumps is that they give rise to a pulsating action on the specimen. This is to some extent true, but it is a difficulty which can be met by pumping up the accumulator before a test, stopping the pumps during the test, and working only from the accumulator; as soon as the test is complete, the pumps can be started and kept going during the interval preceding the next test. Another objection to the pump system is that in this case the supply of water to the straining cylinder must be directly controlled, and, as the water pressure gets as great as 2 or 3 tons per sq. in., it will readily be understood that the valve must be under perfect control, and in order to easily manipulate the floating beam, the lever controlling the valve spindle must be of large radius. Two consecutive valves are better than one.

The above remarks apply equally well to all kinds of testing machines.

THE BUCKTON-WICKSTEED 100-TON VERTICAL MACHINE.

31. A better known one than the 50-ton machine which has just been described, is the 100-ton machine, also designed by Mr. Wicksteed, and made by Messrs. Buckton, of Leeds. The principle and the general arrangement are precisely the same as before. The detailed design varies greatly in different machines, and no two are precisely alike. In addition to appliances for tension testing, most of the more recent machines are provided with arrangements whereby tests in compression, bending, and sometimes torsion, can be carried out. These will presently be described.

In most of the 100-ton machines the main knife edge is supported on the top of a hammer standard, as in the machine last described; in several, a casting resting upon four circular pillars supports the beam.

By this last arrangement the specimen which is being tested is more accessible on all sides, and also it is more convenient for compression tests, where the compression plates are guided in a truly vertical direction by being made to slide upon four planed surfaces formed on the inner sides of the pillars.

In the case of one machine, that at the Yorkshire College, Leeds, the standard, which is of the hammer type, is of exceptional height, its base being some distance below the floor of the testing room. A tension specimen 10 ft. long may be broken in the machine. This machine is so arranged that the operator stands upon a platform which can be raised or lowered in order that readings can be taken at any point on the specimen.

In two, at least, of these machines, namely, that at the Central Institute of the City Guilds of London, and at the Yorkshire College, Leeds, the ordinary capacity is only 50 tons, but by hanging a deadweight at the end of the lever of such a magnitude that it is equivalent to 50 tons load on the specimen, the capacity is increased to 100 tons. When using the machine for loads beyond the 50 tons, the poise weight is first moved outwards until the load has reached 50 tons. It is then brought back to the zero point, the stationary load hung on the end of the lever, and the test proceeded with.

The machines at University College, Liverpool, *Bradford Technical College, and Edinburgh University have

* *Engineering*, 1896.

their levers provided with alternative knife edges. The ordinary fulcrum distance on the 100-ton machine is 4 in., with a poise weight of 2 tons, giving a maximum load, with the full movement, of the weight of 100 tons. If, now, the fulcrum distance can be increased, say, to 12 in., where before a movement of 4 in. meant an increase in the load of 2 tons, now a movement of 12 in. gives the same increase of load, and the maximum load is only one-third of what it was before. By this means a much more sensitive machine can be obtained for light testing. In the three machines mentioned above, this plan has been adopted, and two knife edges provided, either of which may be used. The operation of changing from one knife edge to the other is not a lengthy one, and may be performed with comparative ease.

32. **The Knife Edges.**—The knife edges used in all these machines are made of hardened steel; they are 20 in. in length, and rest upon flat steel plates, also hardened. The maximum load on the specimen being 100 tons, the load on the main knife edge is this load plus the weight of the poise and beam, or rather more than

$$\frac{100}{20} = 5 \text{ tons per in. of length.}$$

33. **Graduation of the Steelyard.**—If the fulcrum distance is 4 in. and the poise weight 2 tons, then differences of load of 1 ton will be given by a movement of the poise weight of

$$\frac{4}{2} = 2 \text{ in.}$$

These 2 in. distances are marked upon a steel scale attached to a beam. They are divided into $\frac{1}{10}$ths of a ton; and further, by means of a sliding vernier attached to the poise weight, into hundredths and two-hundreths of a ton.

34. **Compression.**—So far, the machines which have been described have only been considered as suitable for tensile tests; but, in addition to these, all testing machines of any importance are provided with means whereby specimens may be tested under compressive and bending stresses.

The general principle adopted for the carrying out of these tests is the same in all machines, whether horizontal or vertical, single lever or multiple lever.

On Fig. 25 is shown a side elevation of the standard and holding shackles of a 100-ton Buckton testing

machine. It will be observed, from what has already been said, that the upper gripping shackle suspended from the knife edge in the beam is at A. The second gripping shackle is attached to the crosshead C, and by it the lower end of the tension specimen is gripped. A tension specimen thus held is shown dotted in the figure. The crosshead C can be raised or lowered by two screws D, D, rotated by means of a worm wheel and worm attached to

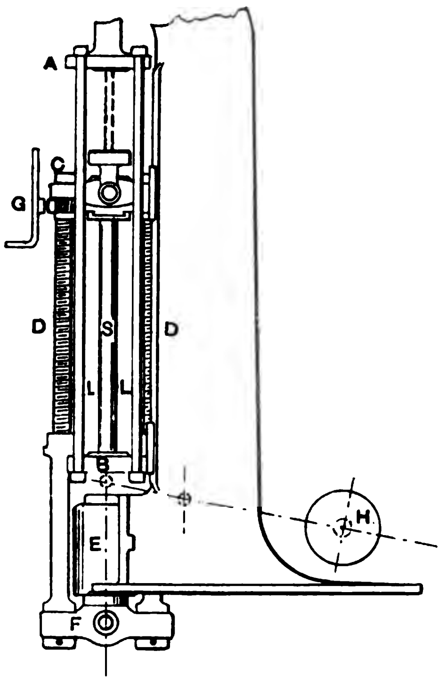


FIG. 25.—Arrangement for a Compression Test.

the handle G. The screws pass into nuts attached to a crosshead, which itself is carried by the ram of the straining cylinder E. So that when the ram is driven out of its cylinder by the influx of the pressure water, the crosshead F, the two screws D, D, the crosshead C, and the lower tension shackle, all move downwards together. The screws are necessary for varying the distance between the shackles, so as to suit specimens of different lengths, and also for tightening the wedges when fixing a specimen in the machine for testing.

So much for tension. When testing in this way the pull from the lever comes through A, and the pull is against the unyielding crosshead C. Precisely the same two parts are used in compression testing, but in rather a different manner. In the diagram, S represents a compression specimen which is to be tested. Its lower end rests upon a plate B; this plate is hung directly from A by four round bars, two of which L, L, can be seen. The upper end of the compression specimen rests against the under part of the crosshead C. So that when a load is applied, it is transmitted through the shackle A and the bars L, L, to the lower plate B, which pulls the lower end of the specimen S *upwards*, and the specimen is caused to press against the crosshead G. As the load increases and the specimen contracts in length, the crosshead C is moved downwards by the ram and in this way the strain taken up. As in the case of tension testing, specimens of varying lengths can be accommodated by altering the position of the crosshead by means of the screws D, D.

35. Transverse Tests.—Fig. 26, which is taken from a photograph of a 5-ton machine by Messrs. Buckton, shows very clearly the arrangement which has just been described. Here, the lower plate B (Fig. 25) is elongated so as to form a support which is used to carry bending specimens.

When a bending test is to be performed the beam to be tested is placed upon two brackets, one at each end of the above-mentioned support. These two brackets carry semi-circular steel plates, upon which rest the ends of the beam to be tested. These plates can rotate to a small degree in their bearings, and accommodate themselves to the lower surface of the beam, which becomes inclined as the beam bends under the load.

The load is applied by the pressure of the beam against a dull knife edge attached below the upper crosshead. Here the usual order of things is reversed, and instead of the load being brought down on the centre of the beam as it rests upon fixed supports, the central knife edge is fixed, and the beam is pulled up against it by the lever. As the beam deflects the strain is taken up by the lowering of the crosshead, and the load is measured as before.

The same means as are adopted in this 5-ton machine for transverse tests are employed in the larger machines; in fact this machine embodies all the essential features of the larger single-lever machines, and only differs from them in that it is smaller, and has a correspondingly reduced

capacity, and also that the jockey weight is transversed by hand entirely. In this case the strain is taken up not by hydraulic ram, but by a simple screw and gearing worked by hand.

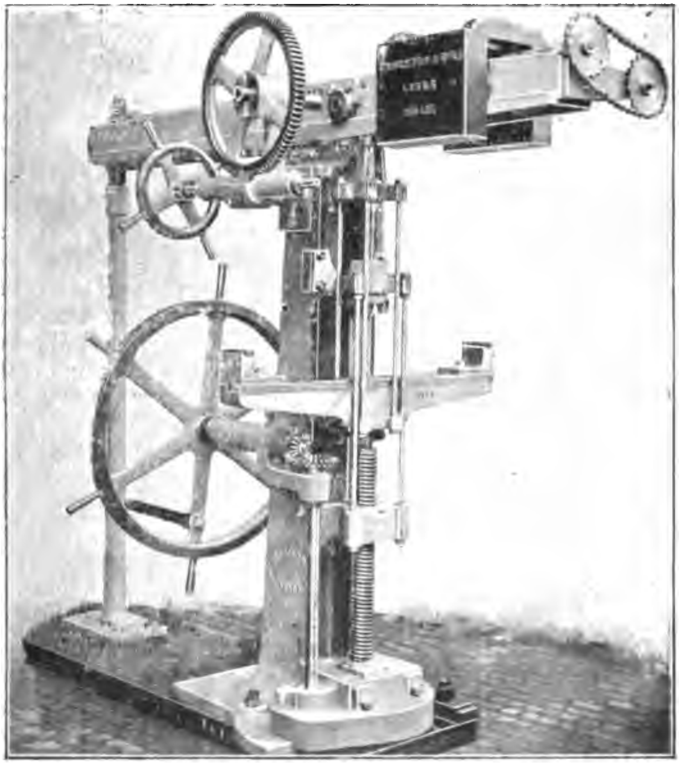


FIG. 26.—Buckton 5-ton Vertical Testing Machine.

36. 100-ton Machine at Sydney University.*—The illustration, Fig. 27, represents a 100-ton Buckton-Wicksteed single-lever testing machine, which possesses several novel features which are worth recording.

This machine, which was built several years ago (1893) for Professor Warren, of the University of Sydney, has a maximum power of 100 tons, and can be used to test bars 10 ft. in length in tension or compression, and is able to test a beam 3 ft. deep, 20 in. wide between supports 15 ft. apart. It is fitted with Wicksteed's alternative fulcra,

* *Engineer*, September 8th, 1893.

which have already been mentioned, and by means of which the maximum capacity of the machine can be made either 100 tons or 50 tons, as may be desired. The main fulcrum upon which the beam rests is supported by four cast-iron pillars, on whose inner sides are slides to guide the upper and lower plates during a compression test. These four pillars, or rather their continuations, extend down to a cast-iron bed placed in the basement beneath the testing room floor. About half way up, or on a level with the laboratory floor, is a steel-riveted girder attached to the four supporting pillars, and carrying at its ends the supports used in the transverse tests.

When a test of this kind is to be carried out, a stirrup is hung from the upper tension shackle; this stirrup carries a V block which rests against the under side of the beam to be tested, and forms the point where the load, as registered by the readings on the lever scale, is applied to the beam—upwards in the centre. The two ends of the beam being tested rest against supports which are carried by the standards at the two ends of the riveted girder. These supports are attached to the ends of two hydraulic rams, working downwards.

The method of testing a beam in this machine is as follows: The beam having been placed in position, the poise weight is caused to move towards the long end of the lever, and the load on the centre of the specimen thereby increased. As the load increases, the specimen deflects, and in order to take up the strain, and so keep the centre of the specimen stationary and the lever floating horizontally, water supplied under pressure from pumps and an accumulator is admitted through a valve into the two cylinders above the ends of the specimen. Their rams are forced downwards simultaneously, and the strain taken up.

It will be seen from the illustration that the standard supporting the two-ram cylinders can be moved inwards or outwards by means of racks and pinions, so that the lengths of the specimens can be varied. By having the direction of the specimen coinciding with the direction of the main lever of the machine, beams of large span can be tested on the minimum of floor space.

37. Rapid Testing Machine.—Fig. 28 shows one of the latest 100-ton machines made by Messrs. Buckton. It is intended for purely commercial work in tension, and is designed for testing a number of specimens in rapid succession. It is actuated throughout by hydraulic

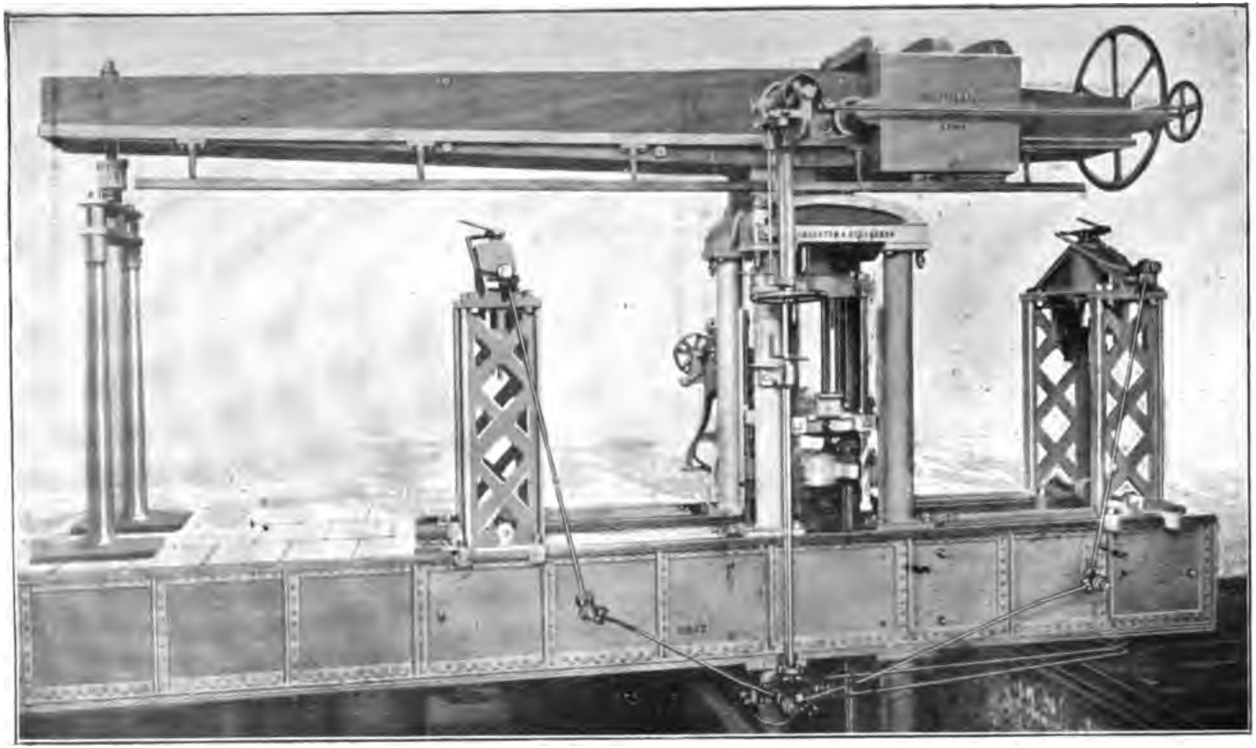


FIG. 27.—100-TON BUCKTON-WICKSTEED MACHINE AT SYDNEY UNIVERSITY.

pressure supplied from an accumulator. The straining is effected by the pressure of this high-pressure water on the upper side of an hydraulic piston. When a test is complete the water is released from the top of the piston and applied to the bottom, so as to cause it to return to its normal position.

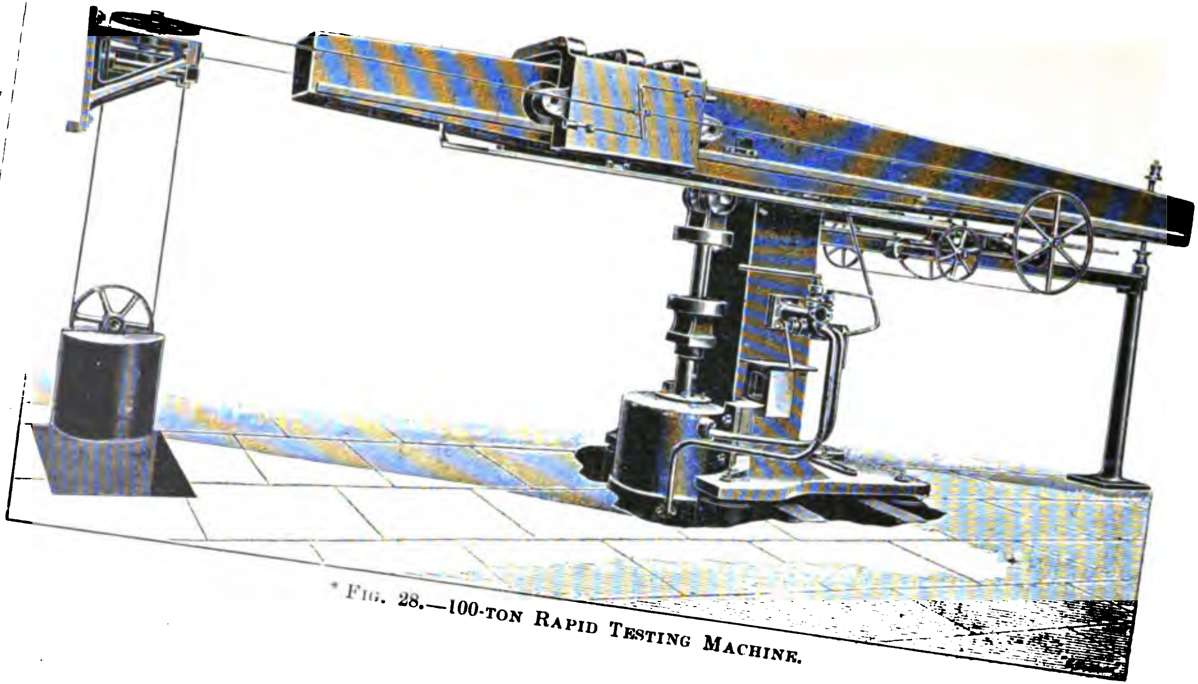
Not only the straining, but the regulation of the load also, is effected by hydraulic means. It will be seen from the illustration that there is a horizontal hydraulic cylinder below the main lever. When the water under pressure is admitted to this cylinder the ram is forced out, and through a simple system of multiplying pulleys and cords, the poise weight is pulled along the beam and the load on the specimen increased. At the end of a test the poise is brought back to its zero position by the balance weight, shown to the left of the figure. A parallel motion on the poise weight keeps the pull of the cords always horizontal, and prevents their tension affecting the load on the specimen. Its use is limited to tension testing. The accuracy of the machine is guaranteed to 1 in 5,000 and it is designed to test with this degree of accuracy samples at the rate of 60 per hour, and a record is said to have been reached with lighter specimens of 120 in the hour! The machine illustrated is in use at the Dowlais-Cardiff works.

HORIZONTAL COMPOUND-LEVER TESTING MACHINE.

By Messrs. Daniel Adamson and Co., Hyde.

38. The two last machines which have been described, namely, the Werder and Buckton-Wicksteed, are both of the single-lever type. We next come to the compound-lever machines, of which the one designed by the late Mr. Daniel Adamson will be described first. The general arrangement of the machine has already been shown on Fig. 19 (*a*). A side elevation of a 100-ton machine of this type is shown on Fig. 29*. The machine is arranged to test specimens in the horizontal position. All the parts are carried upon one cast-iron box framing, so that the machine is quite self-contained. At the left-hand end (as shown on the diagram) is an hydraulic cylinder, fitted with a ram, which moves in an outward direction towards the left. This is the straining cylinder, by means of which the strain of the specimen

* *Journal of the Iron and Steel Institute*, 1888.



* FIG. 28.—100-TON RAPID TESTING MACHINE.

* *Engineer*, October 15th, 1897.

is taken up. In this particular machine the water is supplied to the ram cylinder by means of a set of pumps, which can be worked by power, or manually through the large hand wheel shown in the illustration. The water tank from which the pumps draw their supply is shown at G, and the pumps are immediately at the back of the ram cylinder. At the end of a test the ram is restored to its initial position by the heavy balance weight shown hanging from the chain, the water being allowed to escape from the cylinder into the tank.

Two side rods I connect the ram with the left-hand grip box or crosshead H. The left-hand end of the specimen L is held in this box by means of steel wedges. The crosshead itself slides on the upper planed surface of the bed.

The right-hand end of the specimen L is held in the wedges of a second grip box K, which is connected by a horizontal link with the lower knife edge of the first lever, a steel plate attached to the link resting against the knife edge itself, which is embedded in the lever. In order that there may be no sliding friction between the crosshead K and the bed of the machine, the whole weight of the crosshead and its link is carried by four radial links R, R. This precaution is necessary because it is desirable that the only force registered by the weighing levers shall be the pull on the specimen. The first lever has its two arms at right angles, and these two arms have a ratio of 10 to 1; the second lever is a straight one, also with a ratio 10 to 1; the third is straight, with a 12 to 1 ratio; and the uppermost or fourth registering lever is straight, with a ratio of 12½ to 1. The first three levers are shown dotted in the figure.

The total leverage of this system of compound levers is therefore

$$\frac{10}{1} \times \frac{10}{1} \times \frac{12}{1} \times \frac{12\frac{1}{2}}{1} = \frac{15{,}000}{1}$$

so that to have a maximum load of 100 tons on a specimen it is only necessary to apply to the end of the last lever

$$\frac{100 \times 2240}{15{,}000} = 14{\cdot}9 \text{ lb.}$$

At the end of this lever is a suspending link on which loose weights can be hung. These loose weights are each of the value of 3 lb., the equivalent pull on the

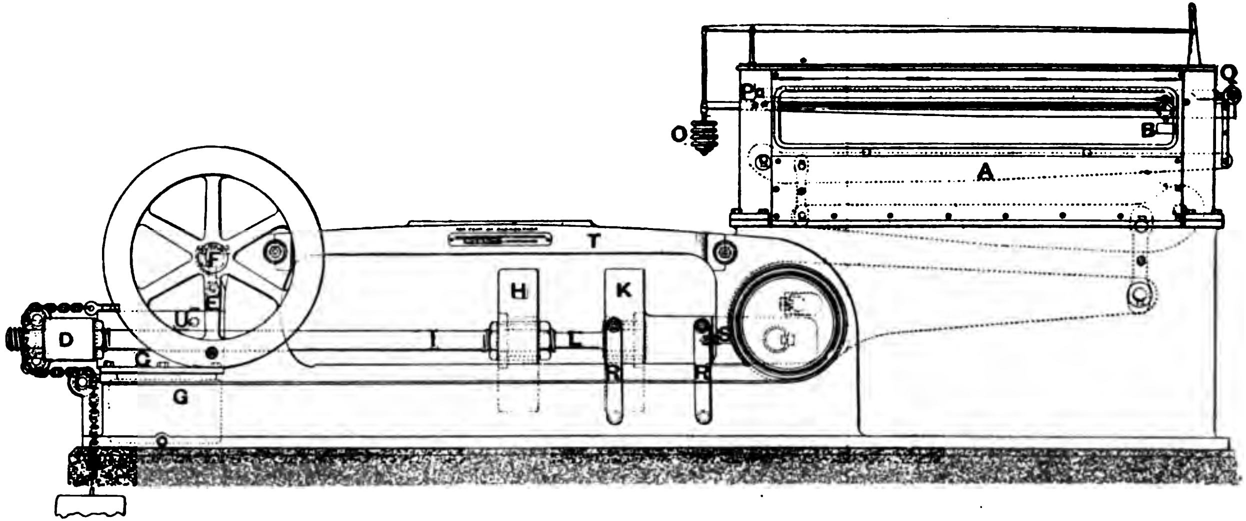


Fig. 29.—Messrs. Adamson's High Power 100-ton Horizontal Testing Machine.

specimen due to a load of 3 lb. at the end of this lever being

$$15{,}000 \times 3 = 45{,}000 \text{ lb.}$$

Hung from the lever is a floating weight B, which is traversed along the lever by a cord actuated by a small hand wheel. This weighs 4 lb., and at the furthest point which it is allowed to reach in running along the beam it is equivalent to 48,000 lb. So that with the four 3 lb. weights, each equivalent to 45,000 lb., in all, 180,000 lb., and the floating weight, equivalent to 48,000 lb., the machine is at its full capacity of

$180{,}000 + 48{,}000 = 228{,}000$ lb. or rather more than 100 tons.

The floating weight, as it moves outwards, traverses a graduated scale on the beam. On this scale the main divisions register 1,000 lb. each; there are also subdivisions indicating 20 lb. each.

When a test is to be commenced the floating weight is placed at zero, and there are no weights on the scale plate. To increase the load the floating weight is traversed outwards until a load of 45,000 lb. is reached. It is now run back to zero and a 3 lb. weight hung on the scale plate. The floating weight is moved outwards again until another 45,000 lb., or a total of 90,000 lb., has been reached. It is now run back to zero, and a second 3 lb. weight hung on to the scale plate; and so on to the end of the test.

It will be seen that the total weight applied when at the full load is only 16 lb. The designer of the machine, the late Mr. Daniel Adamson, contended that by using a multiple-lever machine of high power, very small working weights are required, a machine of great sensitiveness secured, and by having the individual levers of fairly large fulcrum distance, the errors due to inaccurate knife-edge measurements are reduced to a minimum.

In addition to its use for tension tests, the machine can be used for compression, bending, and punching tests, by the addition of a few extra parts.

Besides the four levers, which have already been mentioned, a fifth is sometimes added, not for load measurement purposes, but simply to serve as a pointer, and to enable the operator to detect more quickly and more easily differences of load on the specimen. Such a one is shown in the figure.

In order to protect the levers and knife-edges from dust and dirt and injury, the whole of the right-hand end of the machine is enclosed and the upper part covered

with a glass casing, which can be opened and partly removed when a test is to be made.

HORIZONTAL COMPOUND-LEVER TESTING MACHINE.

By Messrs. Greenwood and Batley, Leeds.

39. The testing machine which has just been described has a combined leverage of 15,000 to 1; that of Messrs. Greenwood and Batley, which we are now about to discuss, has one of about 100 to 1. These are both compound lever machines, but while Mr. Adamson employs four levers, the present machine has only two—one straight and one at right angles. The Greenwood machines are nearly all alike in principle. There are differences in detail and arrangement, according to the kind of work they are intended to be used for.

On Fig. 30 is shown a general view of a 50-ton machine, which is in use at several engineering colleges, government arsenals, and private works.

The machine is a horizontal one, and is arranged to test up to a maximum load of 50 tons in tension, compression, cross-breaking, and torsion.

The arrangement of the levers in these machines is best shown on the diagrammatic view on Fig. 19 (*b*). There are two levers: one a bell-crank lever, whose short vertical arm is attached to the specimen, and whose long horizontal arm is acted upon by the second or straight lever; this second lever carries the movable and variable jockey weight, whose magnitude and position determines the load on the specimen.

Reverting to the general view in Fig. 30, it will be seen that the machine consists, in the first place, of a cast-iron bed, supported on four standards. At the left-hand end of the bed is a frame, carrying the weighing levers; at the right-hand end is a casting consisting for the most part of the straining cylinder. These two castings, one at each end, besides being fixed to the bed of the machine, are further stayed by cast-iron struts fitted between their upper parts.

The straining ram at the right-hand end of the bed works out of its cylinder in a direction from left to right. This ram carries on its end a crosshead, which has attached four screws running from end to end of the machine. A system of spur wheels is arranged on the ram crosshead, the wheels being rotated by the hand wheel shown. There

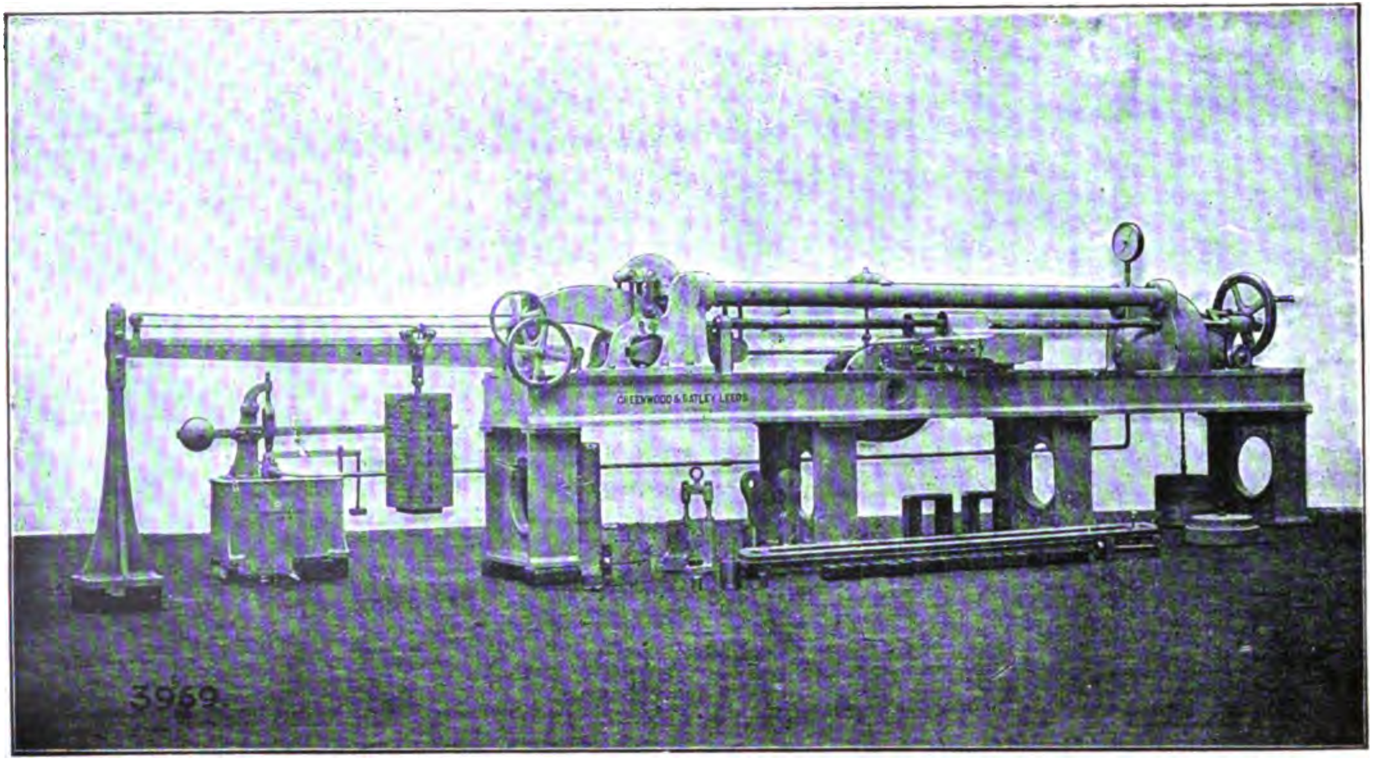


FIG. 30.—50-TON GREENWOOD TESTING MACHINE.

is a wheel on the end of each of the four screws, so that by turning the hand wheel the screws are rotated in their bearings. The nuts in which the screws work form part of the second or movable crosshead. By this arrangement of the screws the movable crosshead can be traversed along the bed plate into any desired position, so as to accommodate specimens of varying length.

The right-hand end of a tension specimen is held by the grips in the movable crosshead; its left-hand end is held in a small crosshead, which is attached by side links to the first knife edge of the first-motion lever.

A tension test is carried out as follows: The movable crosshead is first adjusted into a proper position suitable to the length of the bar which is about to be tested. The bar is then placed in the holding grips, the hand wheel turned, and the screws revolved so as to pull the specimen tight. The load on the specimen is now gradually increased. This is effected by moving outwards, in a left-hand direction, the traversing carriage and its pendant weights by means of the small hand wheel and chain shown. As the weight is moved outwards the force upon the knife edge at the end of the short arm of this straight second-motion lever is increased. This force is transmitted directly to the end of the long horizontal arm of the first-motion lever, and this force again is multiplied and transmitted to the specimen from the knife edge at the end of the short, vertical arm of the first-motion lever through the two side links.

As the load upon the specimen is increased, and elongation begins to take place, the weight lever falls on to its bottom stop, and equilibrium is restored and the strain taken up by admitting a proper quantity of high-pressure water into the straining cylinder. The ram is in this way driven outwards, its crosshead, screws, and the movable crosshead are traversed towards the right and the stretch taken up.

The water used in the straining cylinder is supplied in any suitable way, most frequently by hand pumps or from a power-supplied accumulator.

In the particular machine here illustrated the combined leverage is 112 to 1. The pendant rod carries a number of 50 lb. weights. There are 19 of these in all, and the carriage and scale plate themselves weigh another 50 lb. So that when the full number of weights are in use there is a load of

$$20 \times 50 = 1000 \text{ lb.}$$

acting at a leverage of 112 to 1; or the maximum load the machine can exert is

$$\frac{1000 \times 112}{2240} = 50 \text{ tons.}$$

Any or all of these weights can be used. If the carriage and scale plate alone are used, the range of load is from

$$0 \text{ to } 50 \times 112 \text{ lb.}$$

or from 0 up to $2\frac{1}{2}$ tons; or by putting on the full complement of 1,000 lb. the range is increased, and becomes from 0 to 50 tons. Any intermediate range can be used according to the size and material of the specimen tested.

The graduation of the weighing lever in all the Greenwood machines is in numbers representing the "mechanical advantage" of the load which is being used. For instance, in the present machine the maximum mechanical advantage or leverage is 112 to 1; so that the lever is graduated

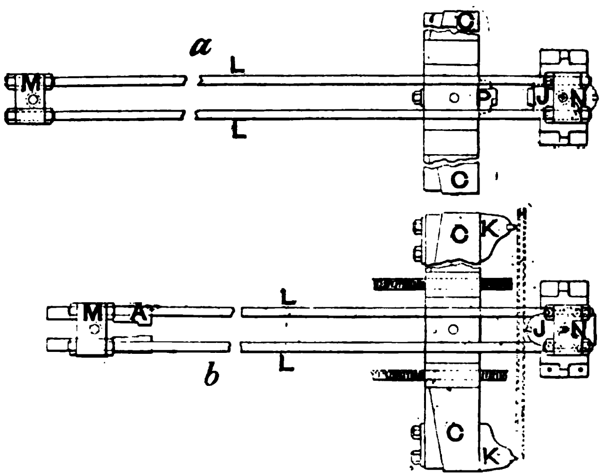


FIG. 31.

from 1 to 112 with intermediate divisions. If the travelling weight which is being used is 500 lb., and the pointer on this weight indicates, say, the figure 60 on the scale, the meaning is that there is a load of 500 lb. acting at a leverage or mechanical advantage of 60. The load on the specimen will therefore be

$$500 \times 60 = 30{,}000 \text{ lb.}$$

Thus, to obtain the load on the specimen the travelling *weight* must be multiplied by the *mechanical advantage.*

When the machine is to be used for crushing or cross-breaking tests, the same principle as the one already described is employed. A third crosshead is put on the bed between the movable one and the straining cylinder; and this is connected by two extra links to the first-motion lever crosshead. So that, when pressure is applied to the ram in the cylinder, the movable crosshead is pulled by the screws *against* the third crosshead through the specimen, the load being measured as before by the force transmitted to the weighing levers through the two extra links.

Fig. 31(*a*) shows a plan view of the arrangement of this machine for crushing. Here M is the small crosshead attached to the first-motion lever linked to the extra crosshead N by the rods L L. The specimen to be crushed is placed between the plates at P and J, J being on the loose crosshead.

Fig. 31(*b*) shows a plan of the cross-breaking gear. M is the small crosshead attached to the first-motion lever. N is the extra crosshead linked to M by the rods L L. The beam to be tested (here shown dotted) rests upon two supports K K at the end of a beam C C, and is pulled against the central V piece at J, attached to N. The beam C C is connected by the screws with the straining ram.

At the end of a test the water is released, and the straining ram brought back to its initial position by means of a chain and balance load, which will be seen hanging beneath the bed on Fig. 30.

This machine has been specially designed for general testing, and for accommodating specimens up to 6 ft. in length. In addition to what has been described, there is a gear provided for carrying out torsion tests. This will be described later.

40. 50-ton Greenwood Testing Machine. Commercial Type, for Shorter Specimens.—This machine is illustrated on Fig. 32. It will be seen that the machine occupies less space than the one last described, in fact it has been designed especially for compactness. It takes in specimens up to 24 in. long in tension, and 12 in. long in compression. There is a beam for testing under transverse stresses whose supports are 3 ft. apart.

Apart from the bed of the machine being shorter than in the case of the machine shown on Fig. 30, additional compactness is obtained by having the second lever, which carries the travelling weight, placed directly above the machine instead of projecting beyond its end. Two links are taken

from the knife edges on the end of the first-motion lever vertically upwards to the knife edges on the short end of the second lever. A downward motion of the jockey weights raises these links, and with them the long arm of the first lever, and so increases the pull on a specimen held in the jaws. The long weight which hangs from the short

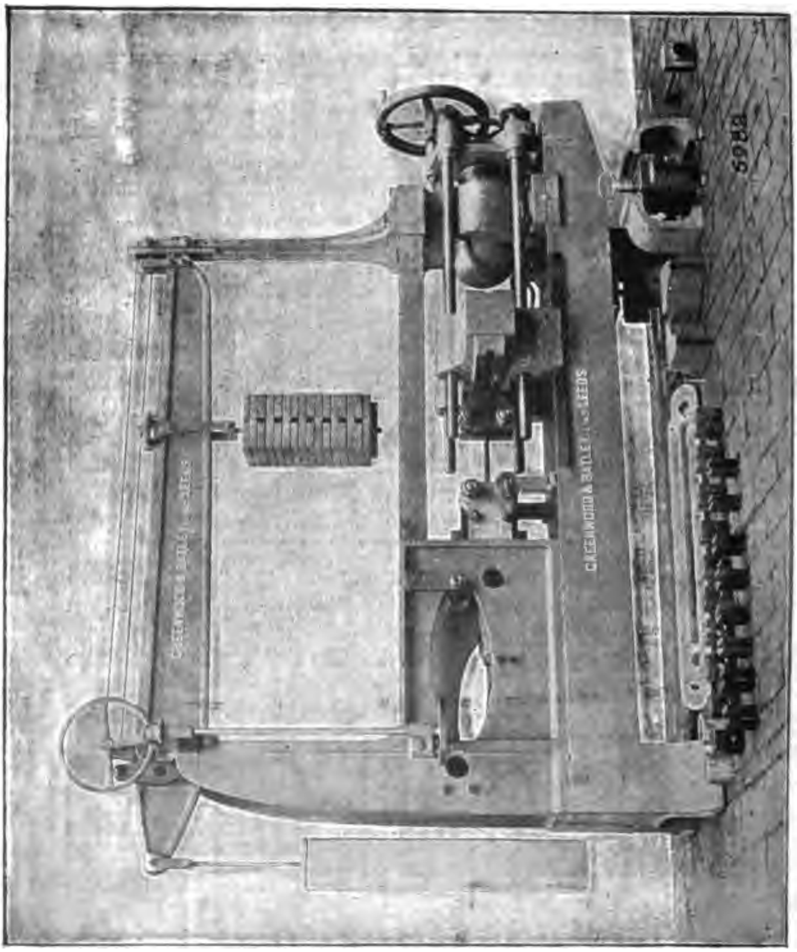


FIG. 32.—50-TON GREENWOOD TESTING MACHINE (COMMERCIAL TYPE).

arm of the second lever is simply a counter poise to balance the weight of the long arm.

The total leverage of this machine is 100 to 1; the

travelling weights are arranged and the readings taken in the way which has already been described.

41. Horizontal Compound Testing Machine by Messrs. Greenwood and Batley to Test up to a Maximum load of 1,000,000 lb.—The machine shown in the accompanying

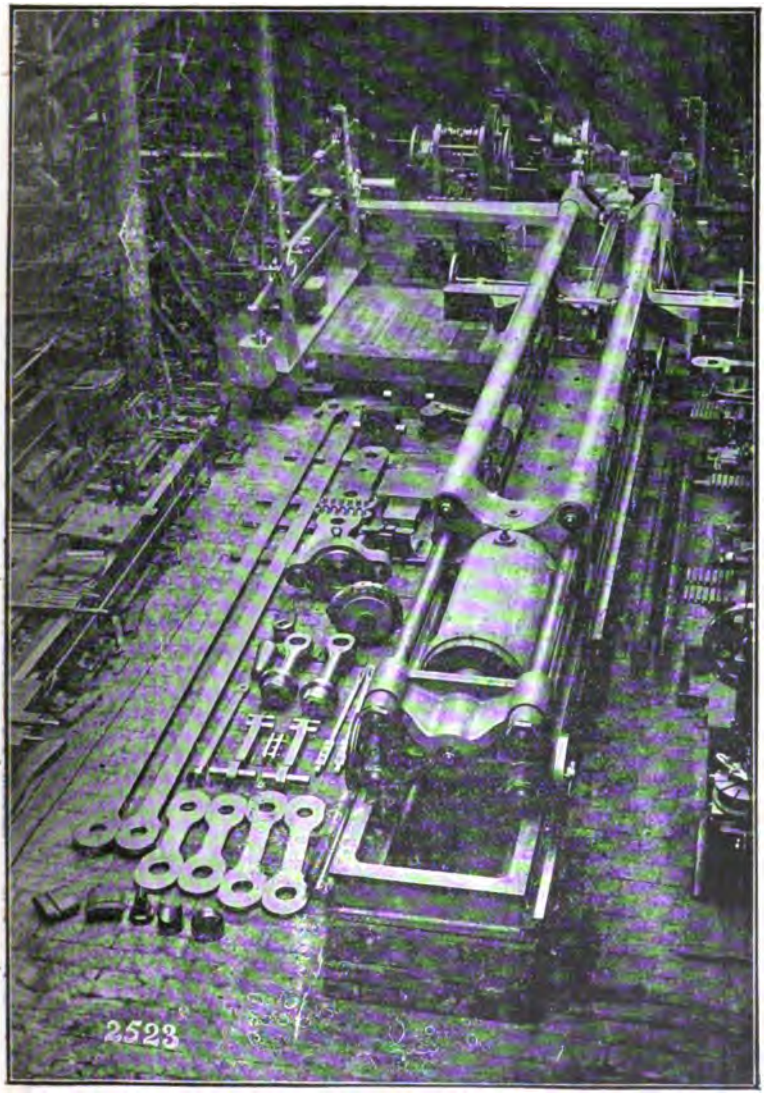


Fig. 33.—The 1,000,000lb. Testing Machine, made for Mr. Kirkaldy.

illustration, Fig. 33, was made, in the first place, to the design of the late Mr. David Kirkaldy, for his now well-known testing works in Southwark. Afterwards a similar machine was supplied by Messrs. Greenwood and Batley to the Belgian Government.

The Kirkaldy machine, as it may be called, is one of the largest machines in use. It has a maximum capacity of 1,000,000 lb., or nearly 450 tons; it is arranged for testing in tension, compression, bending, shearing, bulging, and torsion. The limiting length of a tension specimen is 18 ft. 6 in.

The general plan of the machine is similar to that of the two which have just been described. The straining cylinder will be seen at the extreme left of the machine; its ram has an area of 150 sq. in. and works with water at a pressure of up to 3 tons per sq. in. At the opposite end of the bed is the lever weighing apparatus. The cross-head, which carries the right-hand end of a tension specimen, is suspended upon knife edges by three pendant links, and is linked longitudinally to the knife edge of the first-motion lever. The long arm of this lever, instead of projecting outwards in the line of the machine, stands out at right angles, as will be seen in the illustration. There are altogether three levers, the second and third being carried on a bed or frame placed to the left of the machine and not continuous with it. The outer or long end of the first lever is connected to the short end of the second, which has its arms at right angles, by means of a long horizontal link, and the outer end of the second lever is connected to the short end of the third lever, which is straight, by a short vertical link in compression.

The maximum combined leverage is 2,000 to 1. Both the second and third levers are graduated, and provided with travelling carriages and weights.

HORIZONTAL COMPOUND-LEVER MACHINE.

By Messrs. Buckton, of Leeds.

42. This machine was not included in the general class of horizontal compound machines. It is a comparatively new, and quite distinctive, type; only one or two machines have, so far, been built. There is no doubt, however, that this machine possesses many advantages over previous machines of other designs, which go far to make it one of the best yet produced, and one which probably has a very bright future.

On Fig. 34 is shown a diagrammatic view of this machine. As has been said, the machine is horizontal. The straining is effected by means of an hydraulic ram, A, and the load measured by means of a system of two levers, a straight one B, carrying an invariable jockey weight D, and a bell-crank lever C connected with the short arm of

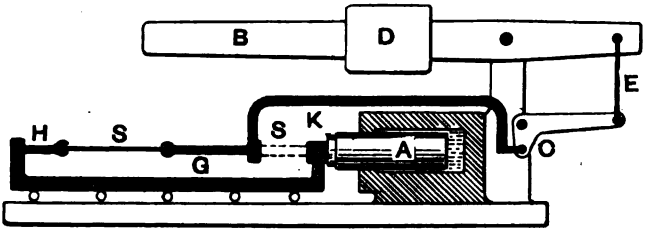


FIG. 34.—Diagrammatic View of Buckton's Compound Lever Machine.

the lever B, by the vertical link E. To the short arm of the lever C is attached, through two parallel rods and cross-head and shackle, the right-hand end of the tension specimen S. This crosshead can be moved along to any required position by rotating the rods, which are screwed from end to end, and so moving the crosshead, which acts as a nut to the screws. So far, the arrangement has not been much unlike many other existing horizontal machines. It is, however, in the part of the machine to be described next that the chief novelty lies, namely, the straining arrangements.

The left-hand end of the tension specimen, S, is attached by means of the usual clips to a crosshead H, which is carried by a massive cast frame G, which itself is continuous with the ram A. This frame is notched from end to end, and the crosshead H can be moved into any required position, and fixed there by means of keys. A second S, shown by dotted lines, is a specimen being tested in compression.

*The first machine of this type was made to suit Professor Kennedy's requirements, to the designs of Mr. Wicksteed, by Messrs. Buckton, of Leeds, and has a maximum capacity of 50 tons.

A later one has recently been made for Professor Elliott, of the University College of South Wales, Cardiff. This is a 100-ton machine, and, in addition to its possible

* *Engineering*, September 12th, 1890.

use for tension, compression, and bending—which are carried out in the manner previously described—provision is also made for tests in shear and torsion.

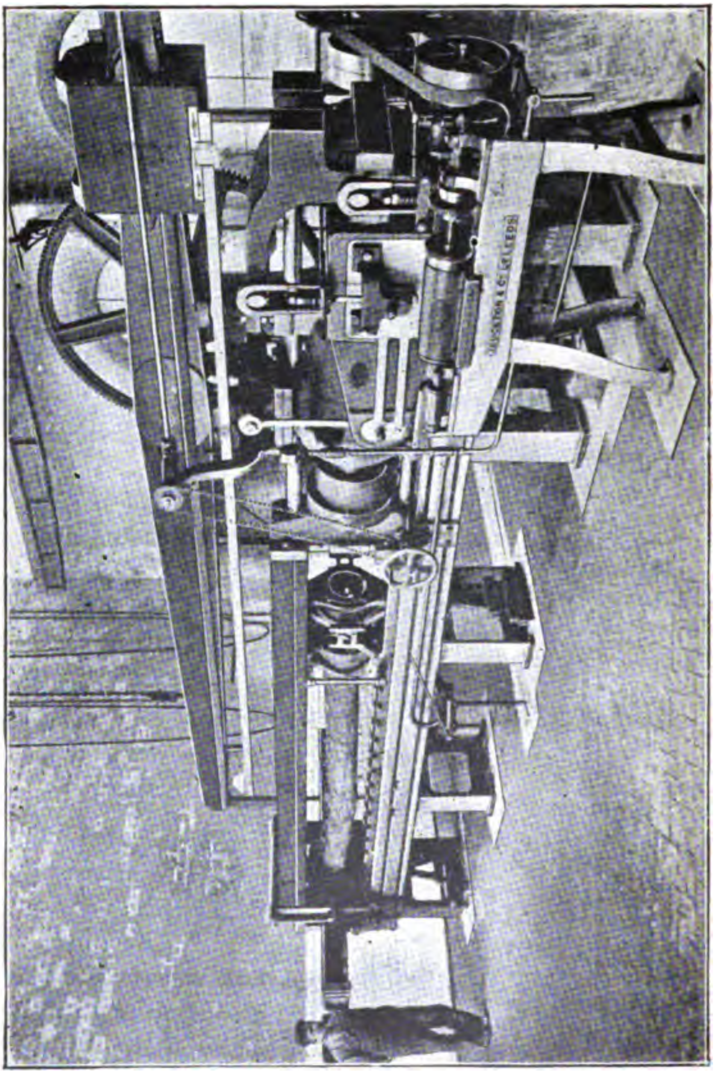


FIG. 35.—100-TON TESTING MACHINE AT UNIVERSITY COLLEGE, CARDIFF.

On Fig. 35 is reproduced a perspective view of the Cardiff machine, showing it in use for a crushing test of a

pit prop. It will be seen that the right-hand end of the specimen is being pressed upon by a crosshead, which is keyed to the ram frame, this latter being forced in a left-hand direction by the pressure of the water. The left-hand end of the specimen presses upon the crosshead, which is attached to the two screws coming from the first knife-edge of the first lever.

The hydraulic pressure is supplied from pumps and an accumulator.

The jockey weight is moved along its lever by a small handwheel and chain gearing. The load on the specimen is indicated in the usual way by direct graduations on the steel scale attached to the beam.

An inspection of Figs. 34 and 35 should bring home two points in which this machine has a great advantage over others which have been described. In the first place

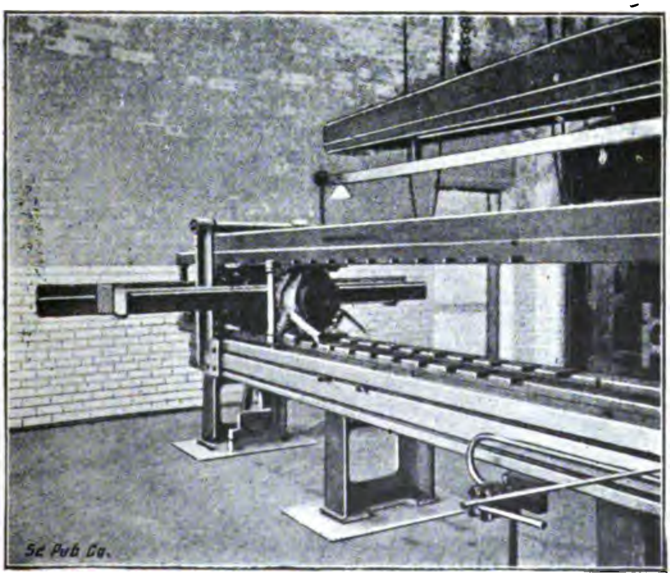


Fig. 36.—View of Cardiff Machine used for Bending Test.

alterations both in the length of specimen, and also in the kind of stress to be applied, can very easily be made; thus, if the specimen S (Fig. 34) has to be replaced by a shorter one, it is only necessary to take out the keys, slide the crosshead H towards the right for the required distance,

and put the keys in afresh. A third crosshead K, which is also capable of sliding along the frame into any desired position, is used for compression tests, and as the middle crosshead can also be moved by the screws, great facilities exist for easy and rapid changes being made. The second advantage possessed by the machine is that the second lever is a long one of the usual Buckton-Wicksteed double-ended design, and provided with a poise weight of invariable magnitude, so that the trouble of changing the loads is avoided and all tests are carried out with the same load. It may also be pointed out that the distance between the weighing levers and the cylinders is shorter than usual, and, therefore, there is less recoil at the point of rupture.

In the 100-ton Cardiff machine the jockey weight is 10 cwt. or half a ton.

Fig. 36 shows a view of the left-hand end of this machine when being used for a bending test.

43. Lesser Machines.—Most of the machines which have been so far described are capable of exerting loads varying from 50 to 450 tons. Such are necessary for testing of specimens of any considerable size, but there are also a great many machines in use for testing specimens of much smaller dimensions and under much smaller loads. One machine of this smaller kind has already been described, namely, the 5-ton machine of Messrs. Buckton. Many other makers turn out smaller machines of various sizes.

Messrs. Greenwood and Batley have built a variety of machines in addition to those already mentioned, varying in capacity from 50,000 lb. to 2,400 lb. The largest of these are of the double-lever horizontal type; many of the smaller ones are of the single-lever vertical type, not unlike the Buckton-Wicksteed design.

Another firm who make small single-lever machines suitable for testing bars up to about $\frac{1}{4}$ in. diameter are Messrs. S. Denison and Sons, of Leeds.

44. Technical School Pattern of Sir W. H. Bailey.—On Fig. 37 is illustrated a small testing machine designed by Sir W. H. Bailey, of Salford, for use in the laboratories of technical schools and for the purpose of illustrating lectures. The machine consists of a cast-iron bed supported upon two standards; of a lever load-measuring apparatus at the left-hand end of the bed; and an hydraulic straining cylinder towards the right-hand end. A tension test piece is shown in position. Its right-hand end is held in wedge grips in

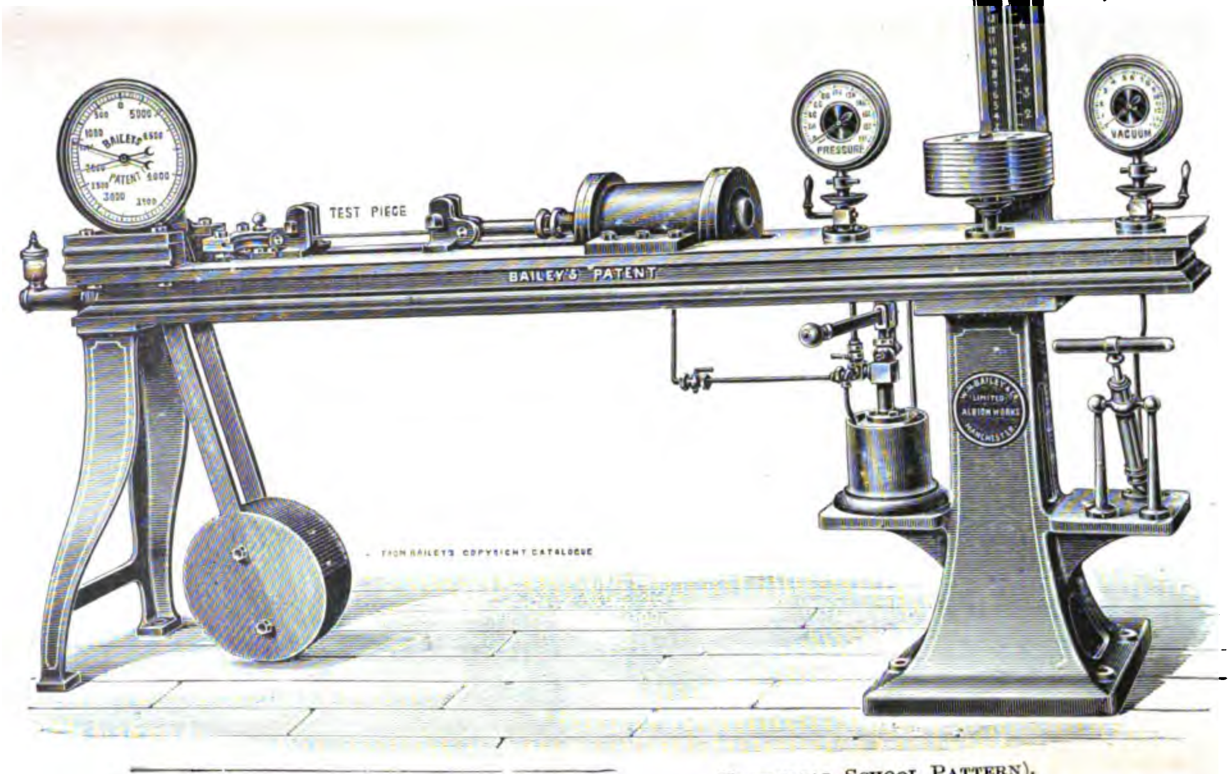


Fig. 37.—Bailey's Small Testing Machine (Technical School Pattern).

a short shackle which is attached to a continuation of the piston rod of the straining cylinder. The left-hand end is similarly held in a shackle, which is linked to the short arm of the hanging lever shown below the bed of the machine. The load on the specimen is applied by pumping water from the small hand pump shown, into the straining cylinder. This puts a pull on the specimen, which pull, when it is applied to the lever, tilts it upwards, the amount of load being proportional to the sine of the angle through which it is deflected from the vertical. This load is directly indicated by a pointer moving over a graduated dial, a second loose pointer being carried round by the first, and left at the maximum load. The graduations on the dial are determined by applying known loads to the lever. The only thing necessary, therefore, in making a test is to gradually apply the hydraulic pressure until fracture takes place. A small oil cataract cylinder is provided to prevent the lever from falling too suddenly when the specimen breaks. Additional parts are supplied for compression and cross-breaking tests

The machine illustrated has, in addition to these ordinary appliances for the testing of materials, some apparatus, shown at the right-hand end of the machine, for testing pressure and vacuum gauges. In some of these machines, instead of an hydraulic straining cylinder, a screw, worm-wheel, and worm are used for taking up the stretch.

These machines are made in two sizes, having maximum capacities of 1,000 lb. and 5,000 lb. respectively, and taking in tension specimens up to 18 in. in length.

45. Ster-Hydraulic Testers.—Sir W. H. Bailey and Co. also make a number of small testing machines for transverse, torsional, and tensile tests, in which the load on the specimen is measured and indicated by the pressure of mercury on a flexible diaphragm, which supports the load in a similar way to that adopted in the Emery machine, already briefly described. The pressure of the mercury is indicated by its height in a vertical tube, as well as in an ordinary pressure gauge. These machines, besides being convenient to use, give very accurate readings.

46. Testing Machines of other Countries.—In testing machines, as in most other things, fashions prevail. Certain machines and certain types of machines are generally popular in one country. In Britain, perhaps,

more than any other country, the variety of types of testing machines is great. Single lever and double lever, horizontal and vertical—all are used. But in other directions there are certain very definite limitations. Manometer or diaphragm machines are not used except for very small loads, and with the exception of machines with a capacity of up to three or four tons, the load is always applied, and the strain taken up by hydraulic means alone. In other countries this is not so. Manometer machines are used to a not inconsiderable extent both in France and the United States of America. In America almost entirely, and to some extent on the Continent of Europe, screw gearing, worked by either hand or power, is used in place of hydraulic appliances for taking up the strain of the specimens.

47. **Continental Machines.**—Of these the Werder machine has already been briefly described. An Alsatian machine, the Grafenstaden, has been largely employed for important testing work. It is made in various sizes, some of the larger ones being arranged as compound lever machines and some as single lever. In the Grafenstaden machines the levers are horizontal, and the specimen placed in the machine vertically; the weighing lever is at the lower end of the specimen, and the appliances for taking up the strain at the top. This latter is of the screw type, the screws used for raising the upper end of the specimen being drawn upwards by large nuts rotated by power-driven gearing. The jockey weight is moved along the weighing lever by means of a screw.

Another machine, known as the Thomasset machine, depends for its load measurement on the fluid pressure in a closed diaphragm, which is pressed upon by the end of the long arm of a single lever of the second order, whose fulcrum is at the other end, and whose third point is attached to the upper end of the vertically-held specimen. The lower end of this specimen is pulled downward by the water pressure on an hydraulic piston.

48. **American Machines.**—These are mostly compound lever and screw gearing machines. Formerly hydraulic power was employed for taking up the strain, but this method has given place in most instances to the use of screw gearing for effecting this purpose. A number of manometer machines as exemplified by the Emery machine are also in use. These are said to possess both great accuracy and extreme sensitiveness, but are not

considered so suitable for the rougher kind of commercial work as lever machines.

Of the lever machines the most generally used and popular in the United States are the "Fairbanks," the "Olsen," and the "Riehle" machines.

The **Fairbanks** is a vertical machine with a screw gearing attached to the bottom of the specimen, for the purpose of taking up the strain, and a compound lever weighing apparatus for measuring the load. The **Olsen** machine, whose arrangement is shown diagrammati-

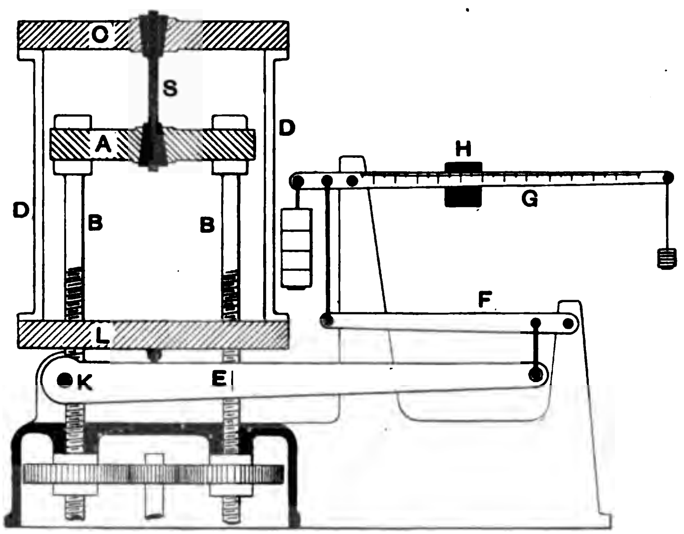


FIG. 38.—Diagrammatic View of Olsen Testing Machine.

cally on Fig. 38, is carried on a small square bed plate of box pattern. In this bed plate is carried the gearing used to give motion to four vertical straining screws, which carry the lower crosshead, and draw it downwards when it is desired to take up any stretch which may have occurred in the specimen under test. The gearing is operated in the first place by means of a pair of power-driven pulleys.

By means of various arrangements of pulleys, the movable crosshead can be moved either up or down, and either at a fast or slow speed, the slow speed being obtained

by means of friction gearing. The motion given to the driving pulleys is further transmitted through spur and bevel gearing to the four vertical screws B B, which, on being rotated, move the lower crosshead A either up or down, as may be desired. The lower end of the tension specimen is held in steel wedge grips, carried by this crosshead A, while its upper end is held by a similar set of wedges in the upper crosshead C. This second crosshead is supported on the ends of four vertical pillars D D, set in the corners of a square. These pillars are rigidly fixed to a casting at their lower ends, and thus serve to transmit the force applied to the upper crosshead to the first measuring lever E. This is a lever of the second order, with its fulcrum at K. The end of the long arm of this lever is connected, by means of a short link in tension, to the second lever F, which is also of the second order. This again is connected by a long link to the short arm of the third lever G, which is a lever of the first order. On this last lever hangs the jockey weight H, whose position on the lever determines the magnitude of the load on the specimen. The jockey weight is moved along its lever by means of ascrew, which is under electric control in such a way that when the beam lifts, owing to excess of load, the weight is set in motion and equilibrium restored. By this means the whole system is automatically kept in balance.

When compression tests have to be made, a compression block is attached to the under side of the movable plate A, and the specimen to be crushed is placed between this block and the table L, which serves to transmit the load to the weighing levers. Similarly for cross-breaking tests a V piece is fixed to the crosshead A, and the beam supports to the weighing table L.

The Olsen machine, as thus briefly described, may be taken to be typical of most of the machines which are used to any great extent in America, chief among these being the machines of Riehle and Fairbanks. They are all made in several sizes, to suit the kind of work for which they are intended. Autographic gears are attached to many of these machines, for the purpose of automatically recording the results of the test as it proceeds.

The **Emery** machine was originally invented by Mr. A. H. Emery, for use in the U. S. Arsenal, at Watertown, Mass. The makers are now Messrs. William Sellers and Co., of Philadelphia. The great advantages possessed by

this machine are its absolute freedom from friction, the ease and speed with which it can be manipulated, and the fact that it works with equal accuracy when testing either large or small specimens. The machine consists of three essential parts, namely, the straining-head, the weighing-head, and the lever-weighing apparatus. The specimen, which is held horizontally, is gripped at one of its ends by wedges held in a cross-head, which is attached to the rod of a hydraulic piston. This works in a cylinder carried by the straining-head. The other end of the specimen is held in a cross-head, which is connected to the movable plate of the weighing-head. When a load is applied to the specimen by the water pressure on the hydraulic piston, the above-mentioned movable plate is pulled against a fixed plate, or rigid support. Between these two plates is what is essentially a thin metal diaphragm or sac which is hollow, and about $\frac{1}{8}$ in. thick. This diaphragm, whose area is large, and supports the whole load on the specimen, is filled with a mixture of alcohol and glycerine. The load on the specimen induces a certain pressure in the liquid, which is transmitted along a pipe to a similar, but smaller, diaphragm, which is made to act upon the small arm of a system of compound levers. In one of these machines the total leverage of the lever system is 16,000 to 1, and the ratio of the areas of the two diaphragms is 20 to 1; so that a weight placed on the end of the last weighing lever induces a load on the specimen 320,000 times as great as itself. It will be seen from this that to have a load of 100 tons on the specimen, it will only be necessary, owing enormous leverage obtained, to place a load of something like 10 oz. at the end of the last lever. The "Emery" machine is thus a compound-lever machine with three mechanical levers and one hydraulic lever. It is said to possess great sensitiveness, and its readings are said to be accurate beyond the requirements of ordinary work.

COMPARISON OF VARIOUS TYPES.

49. It is not possible, for several reasons, to say definitely that one testing machine, or one type of testing machine, is better than another. Testing machines are used for a variety of purposes. There are machines in use in many of the iron and steel works throughout the country; these are chiefly used for carrying out a succession of comparatively crude tests on specimens which do not vary to any great extent

as to their properties or size. In many of the general testing laboratories, the machines have to cope with a great variety of work, both in size, material, and the nature of the tests. Some machines are primarily intended to be used in carrying out important and specially accurate research work; others for educational work almost entirely. In those machines which are provided in many college laboratories, the work to be performed in them comprises almost all the varieties which have been mentioned, especially if commercial work is undertaken.

In comparing the different kinds of testing machines, it must therefore be borne in mind that every kind of testing work does not demand the same qualities in the machines used to carry it out.

If it is impossible for it to be said that one testing machine is better than all others, it is also difficult for one observer to offer perfectly reliable opinions in regard to them. It is given to very few men to have an adequate experience in the use of all the chief types of testing machines; he is almost certain to have a preference for one kind, not because he has a complete knowledge of all, but from an unconscious mental bias, born of use and intimate acquaintance with this one kind.

Bearing these points in mind, therefore, the author proposes to sum up the evidence and present it to the readers, who must themselves be the judges.

There are certain qualities possessed to a more or less marked extent by all testing machines. These are:—

I. Simplicity.
II. Ease of access.
III. Convenience of manipulation.
IV. Adaptability.
V. Sensitiveness.
VI. Accuracy.

The best plan will be to take them one by one, and see how each of the types which have been described stands as regards these qualities.

50. Simplicity.—Simplicity is one of the first and most necessary of the qualities which a designer or a purchaser of a testing machine should insist upon. A multiplicity of parts, however good the result may be, is always to be avoided and always objectionable.

Simplicity is to be desired for several reasons. In the first place the manipulation of a large number of parts in place of a few means loss of time, mistakes are more likely

to occur, and repairs are required more frequently. When carrying out a test on a simple machine the operator has his mind left free to be fully concentrated on the test he is performing. The simpler a machine the less likely it is to get out of order, and the more easily is any displacement, or anything abnormal, at once seen.

It is chiefly in the weighing apparatus that variations as to comparative simplicity are to be found. The straining appliances used in this country are nearly always of the hydraulic cylinder and ram type, and there is little real difference in their arrangement.

In nearly all the English machines the weighing apparatus consists of a lever, or system of levers. The fewer the levers, the simpler the machine. The loads in the specimens are measured by noting the position on one of these levers, of a weight or weights; the simpler machines use a single invariable weight, as against a set of several smaller weights in others less simple.

The two machines which employ single levers are the Werder and the Buckton-Wicksteed. Of these the Werder is prejudiced by the fact that its very small fulcrum distance is the cause of several complications. The Wicksteed single-lever vertical machine is undoubtedly the simplest in all respects. There is only one lever; the fulcrum distance is not abnormally small; there is only one travelling weight, the steelyard principle being adopted in its entirety; and there are only two knife edges to get out of order. One of the great beauties of this machine is due to the fact that the measurement of the load depends on one thing only, namely, the *position* of a weight of fixed magnitude on a straight horizontal lever. There are no calculations needed in order to ascertain what the load really is; the value is given direct, and at once.

In all the compound lever machines the number of knife edges is increased, and the simplicity diminished accordingly. Where variable weights are used, the complication is further increased by the fact that in addition to the trouble involved in the changes, the actual loads can only be arrived at by means of calculations. This variable weight question is one upon which experts differ. Professor Kennedy, for instance, prefers to be able to vary his load so that he can accommodate it to the size and material of the specimen he is testing, and thus use approximately the whole range of the scale beam in every case. Much of the complication of testing machines arises from the fact

that they are often intended for a great variety of tests, both as to the sizes of specimens, and to the kind of stress imposed. If it were not for the fact that a testing machine, especially a large one, is an expensive thing to buy, the ideal arrangement for a testing laboratory would be to have a different machine for every kind of test.

51. Ease of Access to the Specimen.—It is always desirable that the specimen being tested shall be accessible for inspection and the taking of observations during the test. Where the specimens are of ordinary length, there is not much difference in this respect between horizontal and vertical machines. The Wicksteed four-pillar machine is perhaps the one best adapted for obtaining a view of the specimen on all sides, although for some purposes the pillars are somewhat of a hindrance when fixing in the specimen.

Where the specimen is long, there is no doubt that the horizontal possesses many advantages over the vertical type of machine. It is a great convenience to have the whole of the specimen at a uniform and convenient height from the ground, say about three or four feet. The difficulty of testing long specimens in a vertical machine has been partially overcome, in one machine built by Messrs. Buckton, by providing a movable platform which can be raised or lowered to any required height; on this platform the operator stands when taking his observations.

It is sometimes objected that compression specimens tested horizontally tend to sag downwards and always fail by bending in this way. But results would appear to show this to be a fallacy, so far as specimens of the usual dimensions are concerned.

52. Convenience of Manipulation. — When a specimen which is to be tested has been placed in the holding shackles—and more will be said about these later—the application of the pressure and the measurement of the load should be capable of easy and convenient regulation by the operator. The best arrangement is to have, within easy reach of the operator at the same time, two handles—one to control the supply of water under pressure into the straining cylinder, and the other to vary the position of the lever weight. If these two are at different parts of the machine, or if the water is pumped in by hand as it is wanted, an additional assistant will be required. A large single poise-weight, like that used in the Buckton machine, has the advantage in simplicity and in many other ways, but in point of ease of manipulation it falls behind machines of greater leverage and smaller weights.

In all machines the position of the operator should be such that he can work his machine and at the same time have a good view of the specimen, and so be able to note any changes that may be taking place.

53. **Adaptability.**—In all machines used for general work, provision is made for testing in tension, compression, cross-breaking, and often torsion. It is necessary that the change may be easily made from one kind of test to another.

In this respect horizontal are somewhat better than vertical machines, because in the former the heavy parts have only to be moved horizontally along the bed of the machine and not lifted or lowered. What appears to be one of the best machines as regards adaptability is that which was one of the last described, the *horizontal* Buckton-Wicksteed machine, in which changes, both of length and the nature of the stress, can be very rapidly and easily made, and long screwing operations avoided. Next in order come the other horizontal types, and, lastly, the vertical machines. In one respect a vertical machine is always preferable to a horizontal one, and that is when a compression test has to be made of some substance, such as stone, which requires to be bedded in plaster of Paris.

54. **Sensitiveness.**—The measuring apparatus should be capable of indicating very small variations of load. In order that a machine may be sensitive, one essential is that all the knife edges shall be in good condition. If a small load is added to the load on a tension specimen, that increment of load should have the effect of at once moving the lever on which the jockey weight is hung. The resistance which is offered to this motion is almost entirely due to the friction of the knife edges. If these are in good condition, the friction is extremely small, and the sensitiveness of most machines is such that differences of load far less than are required in practical testing cause movements of the lever. But the effect of the continued rolling wear between the knife edges and their plates, and especially of the shocks caused by the fracture of the specimens, is to produce a flattening of the sharp edges and a consequent increase of friction and loss of sensitiveness. This effect is also brought about by the knife edges losing their straight form and becoming slightly curved, and in this way being virtually widened and the friction increased.

A great deal depends on the nature of the steel and on the way it has been hardened, and some machines will lose

their sensitiveness much sooner than others. If it is noticed that a machine is becoming less sensitive, the knife edges must be looked to, and, if necessary, taken out and re-ground.

The results of experiments made some years ago by Prof. Kennedy, on a Greenwood machine which had been used for over twelve thousand experiments, showed that the increment of load required to produce a movement in the last lever varied from $\frac{1}{1250}$th to $\frac{1}{3333}$th of the total load at 5,000 lb. and 50,000 lb. load respectively. In some machines, whose knife edges are quite new and in good condition, the sensitiveness may be $\frac{1}{10,000}$th; while in fluid pressure machines, such as the Emery, still greater sensitiveness is attained.

One ten-thousandth of 100 tons is $\frac{224,000}{10,000} = 22\cdot4$ lb.; so that with this degree of sensitiveness, at the full load of 100 tons, the lever would be moved by 22·4 lb.; this is in excess of practical requirements.

The sensitiveness and practical absence of friction of a good knife edge have been illustrated by Mr. Wicksteed, in a description of a simple experiment which he made on one of his large single-lever machines. He first broke twelve pieces of No. 16 cotton thread, the average breaking load being 3·5 lb.; then, twelve No. 12 threads were broken in the same way, at an average breaking load of 3·8 lb. Pieces of the same threads were then broken by the application of deadweights at precisely the same loads.

In an Emery machine exhibited at Paris it is recorded that a specimen was broken at a load of 90,000 lb., and immediately afterwards a horsehair was put in the machine and broken at the very small load of 1 lb. Mr. Adamson, a few years ago, described how he had found that the recording lever of his machine was sensibly affected by differences in the temperature of a test bar in the machine produced by simply placing his hand upon it.

These few instances serve to show that a degree of sensitiveness exists in most machines, especially when their knife edges are new, which is safely in excess of the requirements of even the most refined tests that are made.

55. Accuracy.—In all testing machines the load, as indicated by the measuring appliances, should be truly and accurately the real load on the specimen. Accuracy is only a relative term—no physical apparatus is absolutely accurate; that is to say, all experimental appliances are liable

to certain errors, some of which are capable of remedy, while some it is, in the nature of things, not possible to avoid.

Let us see to what the errors of testing machines are due. First, there may be errors due to the distances between the knife edges not being accurately measured in the first instance, or to their distances being altered by wear. For this reason levers with large fulcrum distances and small mechanical advantage are preferable to those with very small fulcrum distances: they are easier to measure in the first place, and slight distortion or wear gives rise to a smaller percentage of error than does the same distortion in a lever of smaller fulcrum distance. In the Greenwood machines two levers, each of about 10 to 1 leverage, are used; in the Adamson machine are four levers, each of about the same mechanical advantage: in the Wicksteed vertical machine a single lever is used, with a 50 to 1 leverage. It might be thought that this latter leverage is too great, but it must be remembered that the lever is a very large one, and the fulcrum distance is comparatively great, whereas in the multiple-lever machine the individual levers are smaller, and their fulcrum distances correspondingly so. It must also be pointed out that if there are errors in the first lever fulcrum distance of a compound machine, this error is multiplied by the number of consecutive levers; in the single-lever machine the error cannot be multiplied by any subsequent levers.

The second way in which an error can creep into a testing machine lies in the fact that the weight or weights themselves may be incorrect. A one-ton weight must be exactly one ton, or else it is of no use. All weights used in testing machines, whether great or small, can be and are tested by the Standards Authorities. There is no difficulty with the smaller weights. When it is required to check the larger weights they may be lifted from the machine by chain blocks, and weighed with a suspended weighing machine, which has been previously calibrated with known standards. This should be done from time to time in all machines.

The effect of the friction of the knife edges has already been mentioned. Errors due to this cause are very small, and are practically negligible.

Stresses, which are not indicated, are sometimes caused by inertia forces due to the movement of the machine parts. Theoretically, these are greatest in those machines

with the greatest leverage, but in practice this is not so, because the angular movement of the whole system is so very much more restricted in high-power machines.

It is not only desirable that the errors of a testing machine shall be relatively small, but it should be possible to ascertain whether these errors exist, and what is their magnitude, or in other words, to verify the readings as given on the scale.

In this matter of verification, the vertical machine has a great advantage. It is only necessary to hang dead-weights from the shackles, balance these by altering the position of the jockey-weight, and observe how the scale reading agrees with the actual load.

The accuracy of most horizontal compound machines is made to depend on the accuracy of the knife-edge distances, which are checked by careful measurement from time to time, and on the correctness of the weights themselves, which can be adjusted to a very high degree of accuracy. In some cases special subsidiary knee-levers are provided, so that the leverage can be tested by actual loads hung at carefully determined knife-edge distances.

Another cause of error is due to the fact that the levers of a testing machine deflect slightly under the loads. It is therefore important that the levers shall be designed for stiffness as well as for mere strength. For this reason also high-power levers are clearly better than low-power ones.

It has already been mentioned that the lever should be neutral, that is, that the centres of gravity of the lever and jockey weight or weights should be in the plane of the knife edges. If this is not so it will be found that small errors are introduced, and this is especially noticeable when taking elastic readings, when it will be observed that quite small angular displacements of the beam cause variations to the load, as shown by the measuring gear.

56. Summary.—From what has been said, the reader should be able to draw his own conclusions. So far from any one type of machine being pre-eminently the best, each type has its good points.

The vertical single-lever machine has the advantage as regards simplicity, and ease of verification.

Horizontal machines are best as regards accessibility and adaptability.

As regards adaptability, probably the *horizontal* Buckton-Wicksteed machine is first.

Where sensitiveness, convenience of manipulation, and accuracy are concerned, it is the individual machine, and especially the condition of this machine, which must be looked to rather than the type. If the knife edges themselves are in perfect order, the knife-edge distances and the weights correct, and the balance neutral, one type is pretty much as good as another; and under these conditions the sensitiveness and accuracy of all are in excess of practical requirements.

In conclusion, the writer, without in any way wishing to compare them with other machines, whose high merits he fully appreciates, would like here to express his admiration, after a considerable experience of three individual machines of this type, for the all-round excellence of the 100-ton vertical testing machines, designed by Mr. Hartley Wicksteed and made by Messrs. Buckton, of Leeds.

Chapter III.

AUXILIARY MEASURING APPLIANCES.

57. In addition to the testing machines already described, other appliances are needed for the purpose of taking linear measurements of the test specimens. Such measurements are required both before, during, and after a test. Previous to a test, all the dimensions of the specimen must be carefully determined. Measurements, often of a delicate character, are frequently taken while a test is proceeding, to determine the strains produced by the stresses to which the specimen is being subjected; and it is necessary to carefully measure the specimen after the completion of the test. The instruments used for these purposes may be divided into two classes, namely, those which are used for taking the dimensions of specimens before and after the test, as well as the rougher the measurements taken during the test; and, secondly, those used for taking the minute measurements required during the test, while the material is in the elastic state. These will now be considered separately and in the order mentioned.

58. **Instruments for Measuring Test Specimens.**—The first, and one of the most useful of measuring instruments, is the ordinary *steel rule*. One or two of these are absolutely necessary in a testing laboratory. The most useful length is about 16 in., and, in addition, one 24 in. and one 4 in. long will be found useful. The best way to have the rules divided is into inches on both edges, and to have these inches subdivided into tenths, fiftieths, and hundredths on one of the edges, and into eighths, sixteenths, and thirty-seconds on the other. For all measurements of test specimens, both in and out of the machine, inches and decimals of an inch will be found the most useful units, just as tons and pounds divided into decimal parts are the most convenient units of force in testing work. The ordinary steel rule is most often used in conjunction with a pair of spring dividers, or screw-clamp dividers. A useful size for these is from six to eight inches length of leg. When using the dividers to take measurements on a test specimen in the machine, the two points are applied to two centre-punch marks which have previously been made on the test bar, and then the length so

measured is transferred to the steel rule for a determination of the length in question. For the reason that it is always easier to measure a distance on a rule when beginning from some definite point or division rather than from the end, it is advisable to have the inches numbered from a mark which is not quite at the end of the rule, so that one leg of the dividers can be placed on this mark instead of at the actual end.

When the extensions of very long tension specimens have to be measured, it will be found necessary to have a pair of trammels. These are not so convenient to use as dividers, but they are necessary in some cases.

The dimensions of most metal test pieces should be measured to thousandths of an inch, and for this purpose something more accurate than an ordinary steel rule is required. The two instruments used for this work are the *vernier caliper* and the *micrometer screw caliper.* A general view of the vernier or bar caliper is shown on Fig. 39. It consists of a graduated steel bar having a projecting jaw at one end. This jaw projects at right angles to the main bar, and the object to be measured is placed between this jaw and a second one, which is capable of being moved up and down the bar into any required position. It will be seen that the moving jaw can be fixed in any position by means of a small set-screw at the top. In addition to the moving jaw itself there is a second piece of steel sliding upon the bar, and attached to the sliding jaw by means of a small adjusting screw. This sliding piece can be fixed in any position on the bar, and the sliding jaw moved with respect to it by means of the adjusting screw. By this means the sliding jaw can be roughly moved into position and then finally adjusted into the exact position required by the screw. On Fig. 40 an enlarged view of the fixed and sliding jaws is shown. It will be seen that the bar itself is graduated, and also that the sliding jaw carries a small scale or vernier. In the most convenient arrangement the main scale on the bar is divided, in the first place, into inches; each inch is subdivided into tenths, and each tenth is again subdivided into four equal parts, these being fortieths of an inch. By means of the vernier each of the fortieths can be further subdivided into twenty-five equal parts, these smallest divisions being thousandths of an inch. The twenty-five parts on the vernier correspond in their total length to twenty-four of the smallest divisions on the parent scale. Therefore, each

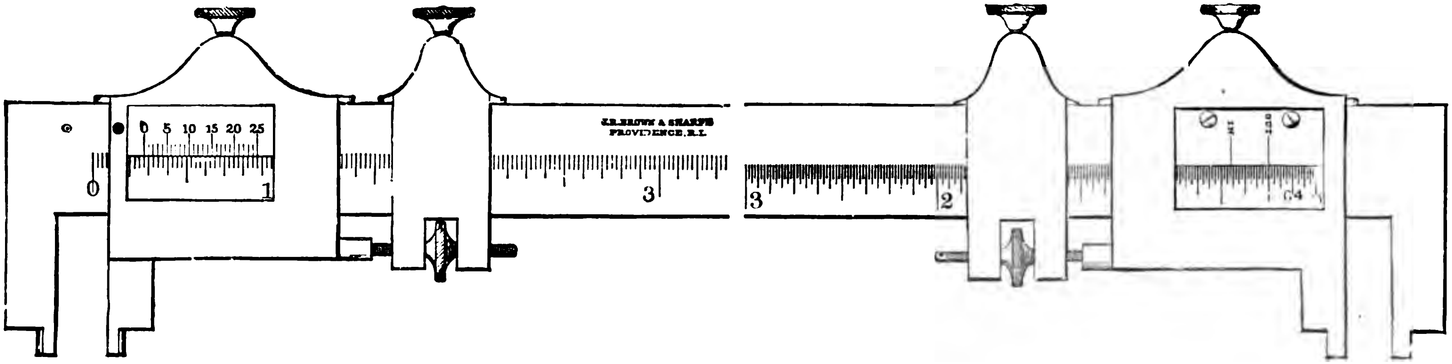


Fig. 39.

of the vernier divisions is one-thousandth of an inch less than one of the smallest divisions on the parent scale. Now, if the accompanying figure be examined, it will be seen that the zero of the vernier scale is at a point on the main scale distant rather more than two-tenths of an inch from the zero of this scale; so that the reading begins with a decimal point, and is followed by the figure 2, representing the two-tenths of an inch, or it reads 0·2 in. Then, following the two-tenths, are three of the smallest divisions or fortieths, so that the reading so far is 0·275 in; each of the fortieths being equivalent to 0·025 of an inch, and as there are three of these, they are represented by 0·075 in. The vernier zero is half-way to the last fortieth, or nearly so, and several more thousandths will have to be added to the existing figures. The zero is twelve-thousandths on, and the figures to be added are 0·012, giving a total reading 0·287. The number of thousandths to be added after reading the fortieths is found by noting the division line on the vernier scale, which coincides with a division on the parent scale, and taking that reading on the vernier. Thus, for the case in question it will be seen that division 12 on the vernier exactly coincides with one of the parent divisions, and each vernier division being one-thousandth of an inch less than each division on the main scale, the meaning is that the zero of the vernier has moved twelve-thousandths beyond the last division. The whole process of measuring the outside dimensions is as follows: First, the screws are loosened and the sliding jaw moved up until the object is roughed gripped; then the separate sliding piece is fixed by means of its set-screw, and the sliding jaw exactly adjusted until both jaws touch the object without either gripping it tightly or allowing it to feel loose. This is done by means of the adjusting screw. The reading is now taken, the order of doing this being, first the inches, then the tenths, next the fortieths or twenty-five-thousandths, and lastly the remaining thousandths, which must be added on.

When inside measurements have to be made with a vernier caliper, the projecting portions at the ends of the jaws are used, and allowance must be made for the combined thickness of these when they are close together. This thickness is always given by the makers of the instrument and generally amounts to about 0·250 or 0·300 of an inch.

Another most useful instrument, especially for small

measurements, is the *screw micrometer*. An outside view of one of these is shown in Fig. 41. The object to be measured is placed between the two straight cylindrical bars, one of which is fixed and the other movable in a bearing at the other side of the horse-shoe frame. The longitudinal motion of this bar is effected by means of a fine pitch screw which is rotated by a knurled thumb-piece, and whose pitch is $\frac{1}{40}$ in. As the pitch of the screw is in., one complete revolution of the milled head causes a longitudinal movement of the measuring bar equal to this amount, and the outer shell being divided into twenty-five parts, $\frac{1}{25}$ of a revolution can be read, that is to say, $\frac{1}{25} \times \frac{1}{40}$, or $\frac{1}{1000}$ in. These micrometers are made in different sizes with capacities varying from 1 in. to 2 in. On Fig. 42 is shown another form of screw micrometer designed for inside measurements only, and capable of reading to thousandths of an inch. A useful size is one having a capacity from 2 in. to 6 in. These instruments will be found especially useful for compression tests.

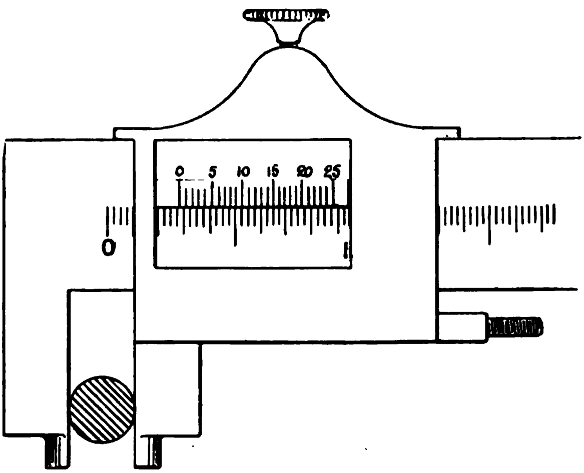


FIG. 40.

It may be mentioned that the chief makers of instruments of the kinds here mentioned are the two American firms, Messrs. Starrett and Messrs. Brown and Sharpe. These firms also make calipers of larger size, graduated to ten-thousandths of an inch. The agents for these instruments in this country are Messrs. Charles Churchill and Co., Finsbury.

59. Measuring Machines. — In measuring the dimensions of test bars smaller divisions of the inch than thousandths are rarely required. For the purpose of making measurements to ten-thousandths, or even smaller subdivisions of the inch, either more precise micrometers, or what are called *measuring machines*, are employed. Both these depend for their working on the same principle as that adopted in the screw micrometer. The earliest machine of this kind was constructed by the late Sir Joseph Whitworth, and exhibited at the Great Exhibition of 1851. This machine consisted of a rigid bedplate, carrying two headstocks, one at each end. The bars between whose ends the object to be measured was placed, were carried by two headstocks, somewhat in the same manner as the centre in the loose headstock of a lathe. They received a longitudinal motion by means of fine-pitch screws rotated by handwheels. The left-hand headstock had a thread of 20 threads to the inch, and the circumference of the wheel was divided into 250 parts, so that by turning the wheel through one

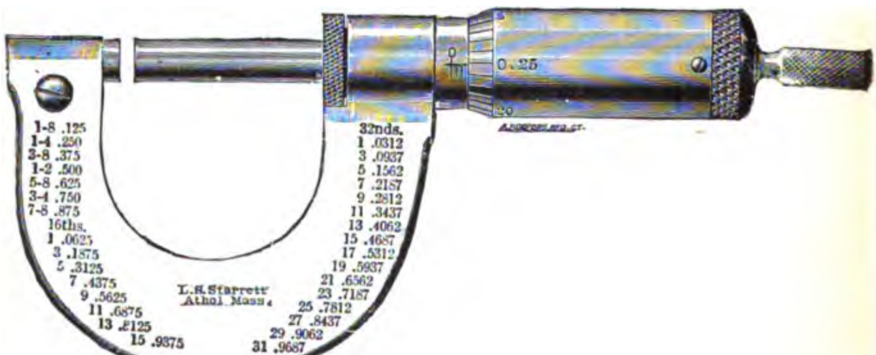


FIG. 41.

division on its circumference, the bar was moved through $\frac{1}{20}$ of $\frac{1}{250}$, or $\frac{1}{5000}$ of an inch. In the right-hand headstock the screw had also 20 threads to the inch. It was revolved by a worm-wheel having 200 teeth, and into this wheel geared a single-pitch worm, which was itself rotated by a hand-wheel, having its circumference divided into 250 parts; consequently, if this hand-wheel was turned through one of its divisions only, the bar in the head-stock was advanced through $\frac{1}{250} \times \frac{1}{200} \times \frac{1}{20}$, which is equivalent to one-millioneth of an inch. But although one millioneth can easily be

read, it does not by any means follow that an object can be actually measured to this degree of accuracy; in fact, it is well-nigh impossible, except by the most practised observers. It is not an easy thing to realise what a millionth of an inch means. Let the reader look at an inch divided into hundredths and try to imagine a tenth of one of these: this will be a thousandth. Then let him try to still further imagine one-thousandth of one of these thousandths: this will be a millionth of an inch. It is almost inconceivable. The smallness of one of these millionths will be appreciated when it is remembered that an inch bears the same ratio to a millionth part of itself as one mile bears to a sixteenth of an inch, or nearly so. It is easy to measure to a thousandth or even a ten-thousandth of an inch; it requires a much greater delicacy of touch and skill to measure to one hundred-thousandth; in fact, there are few people who are capable of it. But when it comes to measuring to so great a degree of precision as a millionth, the observer has a task before him which is well-nigh impossible of achievement. The only way a millionth can be detected is by a slight difference of touch. The effect of the warmth of the observer's hand is quite sufficient to cause this difference. So that it will be seen that

FIG. 42.

for testing, as well as for almost all other purposes, measurements to so great a degree of accuracy as involve millionths of an inch are not necessary, and at the same time are most difficult to carry out. A much more workable and serviceable machine for ordinary purposes than that just described is one, also made by Messrs. Whitworth, which is capable of making measurements up to ten-thousandths of an inch. The fine pitch screw of this machine has 20 threads to the inch, and the hand-wheel used to rotate this screw is of a large diameter, and has its circumference divided into 500 equal parts. One of these divisions therefore corresponds to $\frac{1}{500} \times \frac{1}{20}$, or $\frac{1}{10000}$th of an inch. Such a machine as this will be found very useful for many purposes in a testing laboratory, chief among these being the calibration and checking of other measuring instruments.

Some excellent machines of this kind are made by one or two American firms, who have especially devoted themselves to, and seem to excel in, this kind of work.

60. Bar Calipers.—For the purpose of taking comparatively rough measurements, a pair of short bar calipers will be found useful. These are similar to the vernier calipers which have been described, with the difference that there is no vernier attachment and no screw adjustment, so that measurements can only be made to hundredths instead of thousandths of an inch. They are quickly manipulated, and will be found very useful for many purposes.

EXTENSOMETERS.

61. It is necessary in almost all kinds of tests to take measurements of the elastic deformations or strains produced by the stresses applied. In most specimens of ordinary size these strains are extremely small, and consequently the instruments used for measuring them require to be specially adapted for exhibiting minute changes in the dimensions of the specimen. In the simplest and most frequently performed tests, namely those in tension and compression, it is alterations of length which have to be recorded, and the instruments used for this purpose are called *extensometers*. Some of the more important of these will now be described. There are many different extensometers in use, almost every experimenter having his own particular design. In order to understand what are the necessary requirements to be fulfilled by an extensometer, consider a tension specimen having eleven inches clear length between the holding shackles. We will suppose loads to be applied which do not exceed the elastic limit. In the case of the metals a bar is stretched to somewhere about one thousandth of its own length before the elastic limit is reached. If the length upon which measurements are taken is 10 in., as would be convenient in the present case, the whole elastic stretch of the bar will be one thousandth of ten inches, that is to say one-hundreth of an inch, so that the actual alterations of length due to comparatively small increments of load will be small fractions of one-hundredth of an inch. It is found that it is necessary in most cases to be able to read extensions to thousandths and ten thousandths of an inch. These are very small quantities, which cannot be read by ordinary means, and some method must be employed by which they can be rendered visible to the eye. This is

effected in various ways, by means of—

Wedge gauges.
Lever multiplying arrangements.
Micrometer microscopes.
Optical multiplying devices.

62. Wedge Gauge.—The method of using the wedge gauge is shown on Fig. 43. Here A B is a test bar whose length between two points C and D requires to be measured.

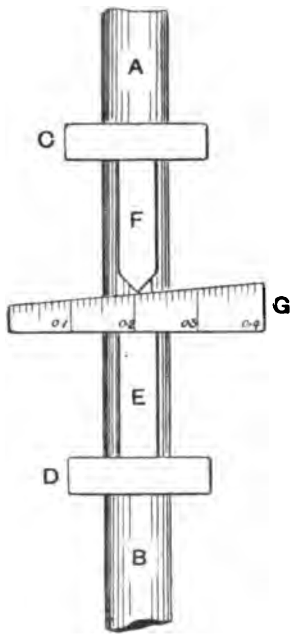


FIG. 43.

Clips E and F are fixed to the bar at these two points. Of these, E terminates in a flat square end, and the other one, F, in a pointed end. Between these two the gauge G is inserted. As the bar stretches these two ends are separated, and the gauge can be pushed further in. If the slope of the gauge is one in ten, a horizontal movement of the gauge of one inch will correspond to a vertical movement of the points of the clips of one tenth of one inch. The graduations are on the upper edge of the gauge, and the slope of the gauge being one in ten, the smallest reading which can be taken is a tenth of the smallest division on

the graduated edge. This is usually either a hundredth or fiftieth of an inch; so that thousandths or five-hundredths can be read. In order that the readings may be accurate, the top of the distance-piece E must be plane and correctly at right angles to the direction of the bar, and also the edges of the gauge must be perfectly straight and free from indentations. In spite of its simplicity the wedge gauge is very little used nowadays, and may almost be described as an obsolete instrument, recent extensometers being capable of more precise readings and, at the same time, more convenient to use.

63. Lever Multiplying Extensometers.—In all instruments of this type the alteration in length of a given portion of the specimen is magnified, so as to be capable of being the more easily measured, by means of a simple lever. This is an arrangement which is at once easy to construct and, at the same time, gives results which are in most cases sufficiently accurate for ordinary purposes. Of the lever extensometers in use perhaps those of Dr. Kennedy are the best known. These include instruments for the purpose of measuring the extensions of both horizontal and vertical tension specimens. Two of these will now be described.

64. Horizontal Lever Extensometers of Dr. Kennedy.*—This instrument is shown in plan and elevation on Fig. 44. In both views, of which the lower one is the plan, A represents the specimen which is under test, held in a horizontal position. At points ten inches apart on the specimen are fixed two clips B′, B″. These clips are each fixed to the specimen by means of two hard-pointed steel screws C, C, and it is really the distance between these that is measured by the magnifying lever. The clips can either be set on two pairs of centre-punch marks, or be simply screwed up lightly so as to grip the surface of the specimen by slightly penetrating into it. They both serve the purpose of fixed distance pieces, and they also form the only supports which the instrument has, as it has no connection or contact with any outside object.

To the clip B′ is attached the hollow triangular plate E′, and similarly, to clip B″ is attached another hollow triangular plate, E″. The end of each base slides upon and is steadied by the opposite clip. As the bar A stretches, the distance B′, B″ increases, the clips move relatively to

* *Engineering*, 1890, II., p. 305.

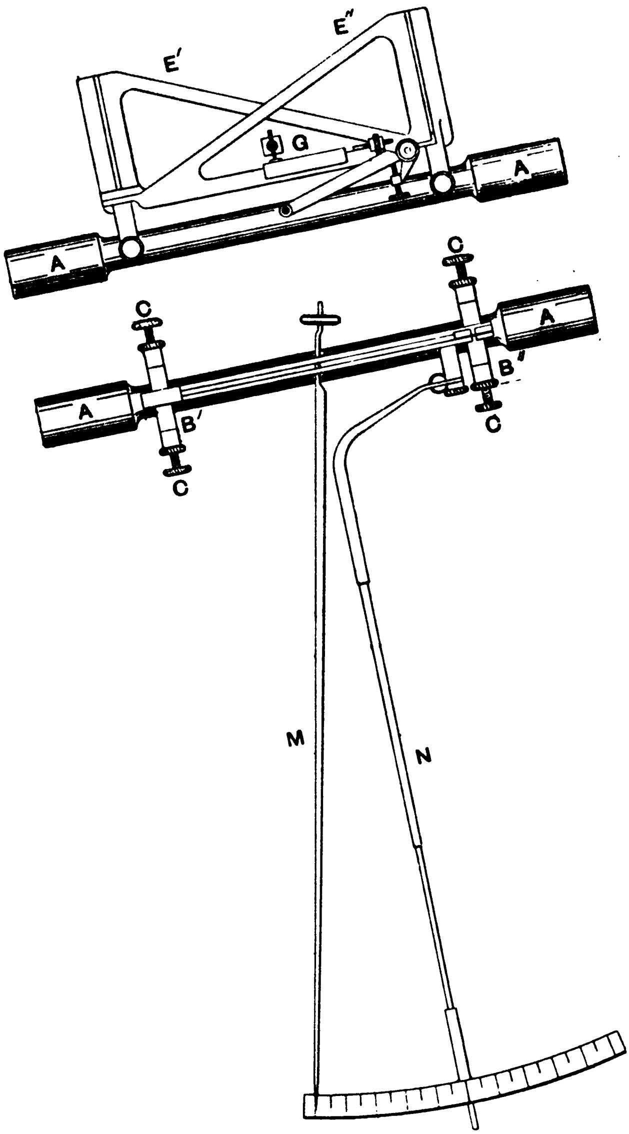


FIG. 44.

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one another, and the horizontal bases of the triangular frames slide past one another to an extent equal to the stretch of the bar between the clips B′, B″. To one of these bases is attached a small plate G, which is capable of being made to slide along the bar, its movement being controlled by a screw adjustment. On the top of this plate is a small cupped disc. A similar cupped disc is carried by the other base, to which it is attached by means of a light plate spring. The cups are arranged so as to be about a quarter of an inch apart, they are on the same level, and their centres lie on a straight line at right angles to the direction of the test bar, and about half way along. These cups move with respect to one another a distance equal to the stretch of the specimen, and this distance is magnified a hundred-fold by the lever M. Corresponding to the two cup discs, there are fixed into this lever two hardened steel points, each of which rests in one of the hollows; the distance between these two points forms the short arm of the magnifying lever; the long arm is 25 in. in length, so that the ratio of the arms is twenty-five to one-quarter, or one-hundred to one. The outer extremity of the lever terminates in a fine point which moves over a graduated scale carried by the rod N, which is attached to the clip B″. The long arm of the lever has its weight balanced by a counter-weight attached to a prolongation of the short arm beyond the suspending points. The scale is graduated into inches and tenths. These tenths of an inch each represent, in stretch of the specimen, one hundredth of one tenth, or one-thousandth of an inch. It is therefore quite easy to read to thousandths of an inch, and as tenths of the smallest divisions can be estimated by eye, it is possible to read to the nearest ten-thousandth. When calibrating the instrument, the correctness of the measurements of the lever arms should not be relied upon, but a direct calibration should be effected by means of a vernier caliper or a measuring machine. When a vernier caliper is used, one clip of the extension gear is fixed to a rigid support. The main bar of the caliper is also fixed to a rigid support, and the second clip made to grip the slide of the vernier. When the apparatus has been fixed in this way, by turning the screw of the vernier caliper its slide is made to move with respect to the bar, and, consequently, one clip of the extensometer relatively to the other one. In this way the pointer of the extensometer is made to move over its scale. At the same time the exact distance moved

is given by the reading of the vernier, and this can be compared with the reading given by the pointer on the scale, and in this way the latter can be adjusted. The best way of doing this, having graduated the scale so as to give approximately the correct readings, is to move the scale inwards or outwards until the reading exactly coincides with the vernier reading. The length of the pointer can then be adjusted to suit the scale.

65. Kennedy Lever Extensometer for Vertical Bars.* In addition to the extensometer which has just been

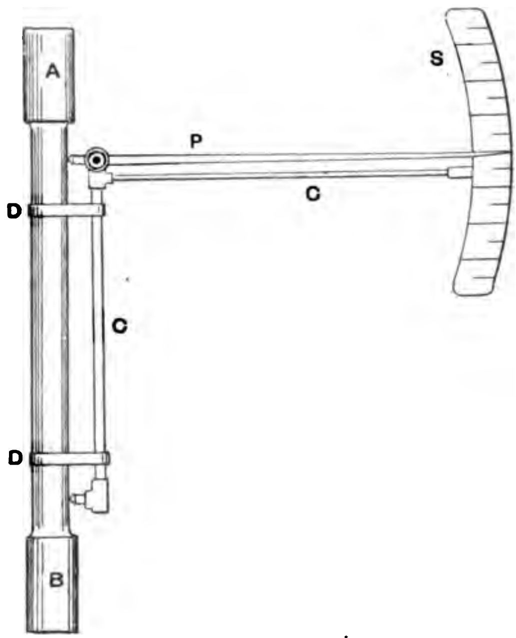
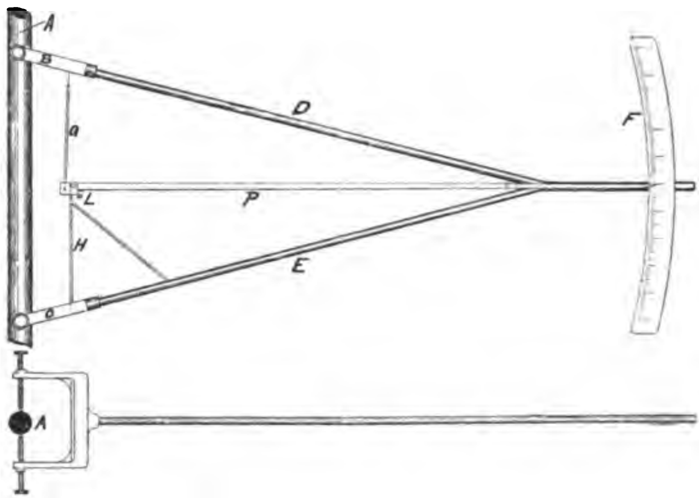


FIG. 45.

descr''ed, Dr. Kennedy has designed and used a somewhat modified form, based upon the same principle, and suitable for use on specimens which are held vertically, as well as horizontally, in the machine. The design is simple, and will be easily appreciated on reference to Fig. 45. Here A B is the test bar; C C is a rigid, right-angled frame, carrying at its outer end a graduated scale S, and, at the lower end of its vertical arm, a centre point, which is held by means

* Min. Proc. Inst. C.E., Vol. lxxxviii.

of a rubber band D in a centre punch mark on the surface of the specimen. The measuring lever or pointer, P, has its fulcrum on this rigid frame, and the termination of its short end is a centre point similar to the one which has been mentioned, and which is also held in a centre punch mark by a second rubber band. As the bar alters in length these two points become separated, and the point of the lever is caused to move down the scale. The calibration is effected as in the former case. This instrument may be relied upon to give accurate readings, but the writer has found that the chief difficulty attending its use is in the attachment. A possible cause of error in this instrument



46.

is due to the fact that the readings given only apply to the length variations of *one surface* of the bar, and not to those of the axis.

66. Goodman Extensometer. — Another instrument of the lever multiplying type is that of Professor Goodman. This instrument is intended for use on vertical test specimens, and consists of a simple lever arrangement. It is shown in plan and elevation on Fig. 46. Here A is the specimen in the machine; B and C are two forked clips, one at the top and the other at the bottom of the specimen; these serve as the means whereby the extensometer is attached

to the specimen. The attachment is made by two pairs of screws, which are made to grip the bar in the centre of its width. Two brass tubes, D and E, fixed to the fork clips, serve to carry the scale F, which is divided horizontally into inches and tenths of an inch. A vertical brass rod, H, attached to the clip C, has a small groove on its end which forms the fulcrum upon which the middle knife edge of the pointer, P, rests. At the outer end of the short arm of the lever is a second knife edge, pointing upwards, and upon which rests a second vertical rod G, depending

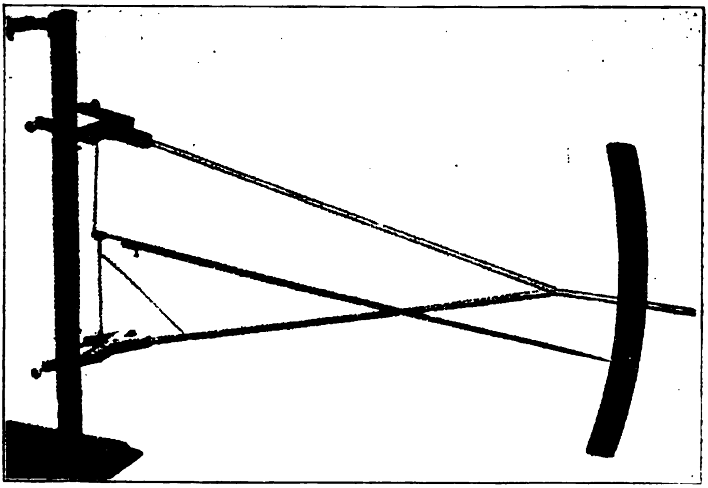


FIG. 47.

from the clip B. The other a[illegible] the lever terminates in a point which moves over [illegible] scale F. The leverage is 100 to 1. When the in[illegible]ment is about to be used the screws are made to lightly clip the specimen at points 10 inches apart; the dimensions are so arranged that this brings the lever nearly horizontal and the pointer at the zero of the scale. An exact adjustment to zero can be made by means of a small screw L below the lever. As the bar stretches, G is lifted upwards and H is lowered, and consequently the pointer descends along the scale. As the leverage is 100 to 1, a vertical movement of the pointer of one-tenth of an inch means an extension of the bar of one-hundredth of this, or one-thousandth of an inch; by estimation readings are easily taken to $\frac{1}{10000}$th of an

inch. This instrument is easily calibrated either by means of a vernier caliper or a measuring machine. Besides being simple and inexpensive to make, it is easily manipulated and very reliable in its readings; the writer can state this from his own experience. It should be mentioned that the pointer is made of wood.

A general view of this instrument is shown in Fig. 47.

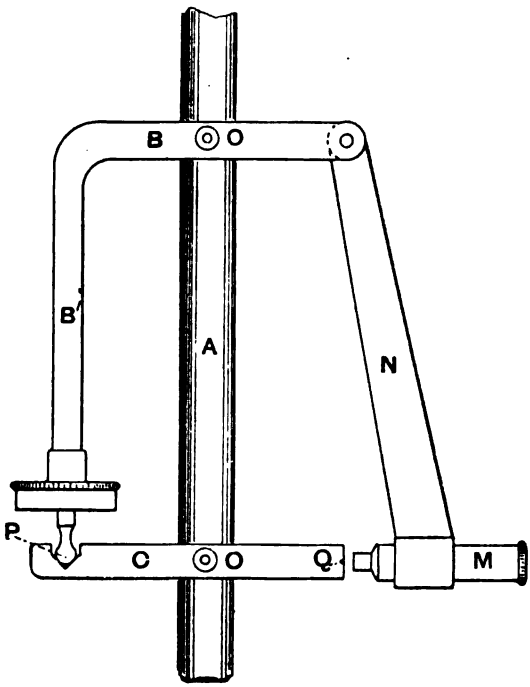


Fig. 48.

67. **Ewing Microscope Extensometer.*** —In this extensometer, instead of the extension of the bar being magnified by mechanical means in the form of a lever, as is the case with the Kennedy instruments, this is effected by the use of a microscope fitted with a micrometer scale. A diagrammatic view of the instrument is shown on Fig. 48. In this figure the test bar is marked A. At two points on the bar O, O, ten inches apart, are fixed, by means of pairs of set screws, two separate pieces B and C.

* Proceedings Physical Society, May, 1895.

These have each only one degree of freedom with respect to the test bar, this being freedom to rotate about the axes of its set screws. To the piece B is attached at right angles the bar B′. The end of this bar is a rounded point P, resting in a transverse V-slot, cut in the other piece C. As the bar extends the lower point O descends with regard to B B^1, the bar C turns about the point P as a fulcrum, and the opposite end of C, marked Q in the figure, is moved in a downward direction also. The extent of this movement is ascertained by observing a mark on Q, by means of a microscope M. An adjusting screw is fixed to

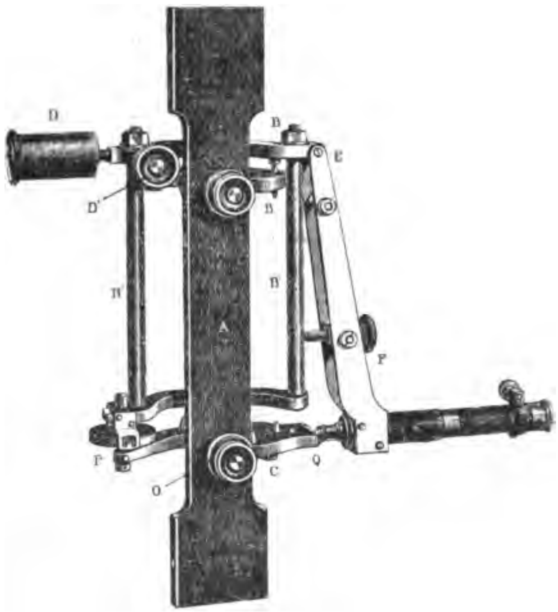


FIG. 49.

the lower end of B^1 for purposes of adjustment of the point Q. The microscope, M, is slung by means of the rod N from the end of the piece B. The movement of Q, as read by the microscope, is not the actual extension of O O, but a multiple of it in the ratio of P Q to P O. On Fig. 49 is a general view of the instrument as applied to a flat test bar. The different parts will be recognised from the above description. In addition to what has already been mentioned there is a counterpoise D, which serves to

balance the weight of the microscope. In this instrument the point B rests in a conical hole instead of a slot.

The object at Q, which is sighted through the microscope, is a fine wire stretched across a hole in a plate, and illuminated by a mirror behind. Readings are taken to one edge of the wire, and a micrometer scale engraved on glass is fixed in the eye-piece of the microscope. In the instrument in question the distance O P is made equal to O Q, so that the movement of Q, as seen through the microscope, is just double the extension of the specimen. The divisions on the scale, and the length of the

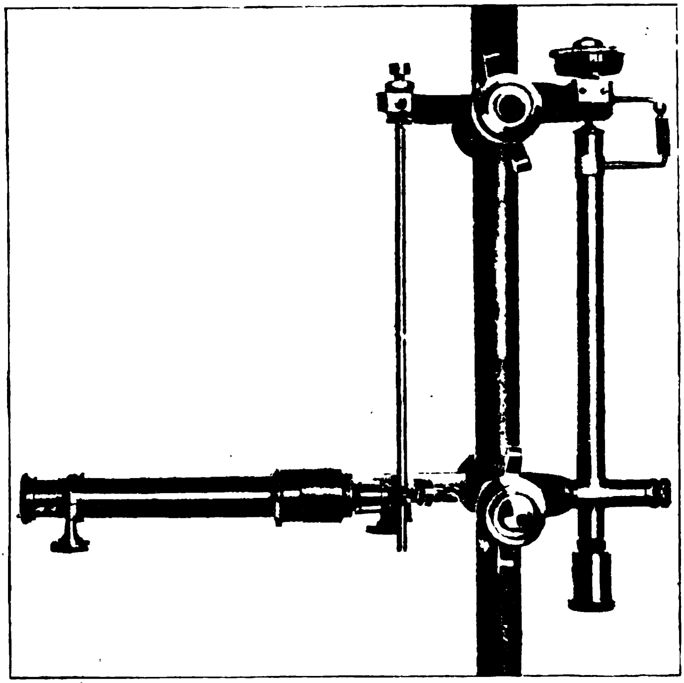


FIG. 50.

microscope, are so chosen that readings can be taken which correspond to $\frac{1}{50000}$ of an inch of extension of the specimen. In order to check the scale readings the screw P is turned through one revolution. The pitch of this screw is $\frac{1}{50}$ of an inch, therefore this one revolution of the screw should displace the edge of the wire at Q through 500

units on the scale. It must here be remembered that Q moves through twice the distance moved by O.

This screw at P may also be used where the extension of the bar exceeds the full range of the scale, when Q may be brought back to zero after the end of the scale has been reached; its use is also necessary for adjusting Q to the zero of the scale. A special form of this instrument is also made for use on the members of actual structures, such as

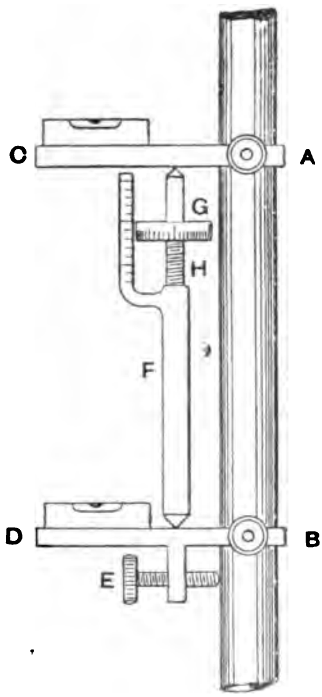


FIG. 51.

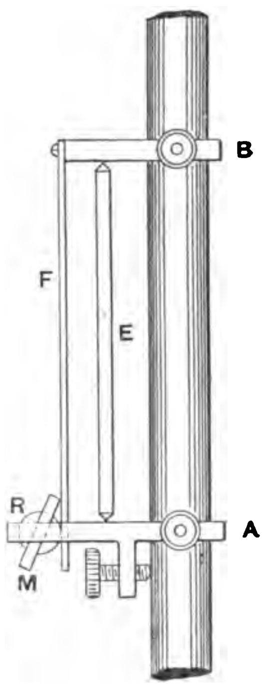


FIG. 53.

the members of roofs and bridges. On Fig. 50 is illustrated the latest form of the Ewing extensometer. This instrument, while making use of the principles adopted in the older forms, differs considerably in detail, and possesses the important advantage that it can be applied equally well to horizontal, vertical, or sloping bars.

68. Unwin Screw Extensometer with Levels*—This instrument, which was designed and has been used by Prof.

* Unwin's "Testing of Materials."

Unwin, is represented by the diagrammatic sketch on Fig. 51. Here the test piece, which is vertical, is gripped at the ends of the portion to be measured by two screw clips A, B. These are maintained horizontal by ordinary spirit levels. placed upon the arms C and D. The arm D is kept in a horizontal position by the small set-screw E, which serves to rotate the clip about its two centre points. The bar C is likewise maintained horizontal by means of the screw distance-piece F, whose lower end rests upon D, and whose upper end presses upon the under part of C. The length

Fig. 52.

of this distance-piece is variable, and can be adjusted by the graduated wheel G fixed upon the fine pitch screw H. As the bar stretches the level on C tends to fall; this is restored to a horizontal position by turning the screw G, and when this has been done the amount of extension is read on the graduated circumference of G. The pitch of the screw and the graduation of the wheel are such that the instrument reads to one ten-thousandth part of an inch. A perspective view of this instrument, as made by Messrs. Nalder Bros., is shown on Fig. 52.

69. Unwin Mirror Extensometer. — The general arrangement of this instrument, Fig. 53, is not unlike that of the one which has just been described. Instead, however, of having a distance-piece of variable

length between the two clips A and B, there is one, E, of fixed length whose ends serve as fulcra, about which the clip B rotates as the bar varies in length; and, in consequence of this movement, the outer end of the clip A moves with respect to the clip B. To B is attached a finger-piece F, which presses against a roller R carried by A. As the bar varies in length this finger-piece, pressing against the roller, causes it to rotate through a small angle. To the roller is attached a small mirror M, and the amount of rotation of the mirror is observed by means of a reading telescope and scale. The graduated scale is placed some

FIG. 54.

distance away from the mirror, and its reflection is observed by means of the telescope. The whole arrangement thus constitutes what may be called a system of optical leverage. It is stated that readings can be taken to $\frac{1}{100000}$th of an inch. A perspective view is shown in Fig. 54.

70. General Considerations.—Many of the extensometers in use are somewhat costly instruments, and it therefore behoves experimenters to consider well the qualities necessary in a good extensometer before proceeding to select one for their own use.

The first quality necessary is *accuracy*. By this is meant that the readings given by the instrument shall indicate really and truly the measurements they represent.

With all the instruments which have been described this accuracy can be relied upon to a considerable degree of precision. In all of them, readings can be taken to one ten-thousandth of an inch in ten inches. This is equivalent to a degree of precision of one in one-hundred-thousand, which is quite sufficient for any ordinary purposes. In the case of some of the extensometers an even greater degree can be depended upon. The writer has tested an extensometer of the lever multiplying kind, by means of a Whitworth measuring machine, and found it perfectly accurate within the degree of precision mentioned.

An extensometer should be so constructed as to be *easily and quickly fixed* to the specimen, ready for the test. Some instruments are very deficient in this respect, and much time is wasted in getting the instrument properly set.

Lightness of construction is an advantage so long as strength and rigidity are not sacrificed. As in testing machines, *simplicity of design* is of the utmost importance. A multiplicity of parts adds to the weight as well as to the cost. There is greater liability to derangement, and the instrument is much more difficult to adjust.

The accuracy of extensometer readings should be made to depend not upon direct measurements of lever ratios, but the instrument should always be directly calibrated in the manner already described; and, moreover, this calibration should be repeated occasionally so as to make sure that the adjustment has not been disturbed.

In using an extensometer it is important that it be fixed on the proper part of the test bar; otherwise the readings obtained may be inaccurate. Many test pieces are initially curved to a slight extent, and, as the load upon one of these is increased, it not only stretches but tends to straighten at the same time. The effect of this straightening is an unequal strain on the two sides of the bar; the straightening will have the effect of, to some extent, counteracting or lessening the stretch of the bar on its convex side and increasing the stretch on the concave side. If, therefore, the measurements be taken on either concave or convex side, they will be rendered inaccurate by the straightening of the bar; a similar effect is sometimes produced by the load upon a bar not being applied centrally, and the consequent curving of an initially straight test piece. It has been shown by Professor Unwin that either of the effects mentioned will be accompanied by

approximately accurate results, if simultaneous readings be taken with two extensometers, one placed on the concave and the other on the convex side of the bar, and a mean of these two sets of readings taken. Such a plan has been very successfully adopted by Professor Bauschinger, who has used two roller and mirror instruments: with this arrangement he has been able to take measurements of the elastic extensions of test bars which have probably never been exceeded in accuracy. Mr. Strohmeyer has, in a similar way, made use of two roller extensometers working with pointers instead of mirrors.

If, instead of employing two extensometers, only one be used, fixed by two pairs of set-screws midway between the two sides or opposite the axis of the bar, readings will be obtained which are not very far from the correct ones, and the same result will be obtained as if two instruments had been used. This plan has been adopted in the great majority of the more recent extensometers.

Up to three years ago nothing very definite had been done in the way of comparing extensometers of different kinds. This has now been done by a Committee of the British Association, consisting of Professors Kennedy, Ewing, Capper, Beare, and Unwin.* The conclusions arrived at are contained in a report published in 1896. This committee prepared bars of steel, arranged in four sets of three. Each set consisted of a flat bar of mild steel, 2 in. by ½ in. in section, and two round bars of special steel, 1¼ in. and ¾ in. diameter respectively. Two sets of these bars were circulated among seven observers who had undertaken to make measurements for the committee. The extensometers used included micrometer microscopes, lever multiplying arrangements of different kinds, and one mirror extensometer. In carrying out his observations each experimenter was required to make certain definite measurements at stated loads, and send in his results on special test forms drawn up by the committee.

The preliminary measurements of the areas of the bars by the different observers compared very favourably, and showed that the error of measurement very rarely exceeded about one-fifth of 1 per cent from the mean value given by several observers, while the difference for any two observers in some cases reached one half of 1 per cent.

In the measurements of extensions for increments of load of one and a quarter tons in the smaller bars, and

* British Association Report, 1896.

two and a half tons in the larger ones, the variation of the maximum and minimum values obtained by any one observer are rather large, and in many cases exceed 5 per cent. This large error is not so bad as it would seem when it is remembered that the extensions were those corresponding to very small increments of load, and also that many of these maximum and minimum errors were probably accidental ones. Each observer calculated the modulus of elasticity of the bars from the results of his experiments. If the mean value of this modulus for all loadings by all observers for each pair of similar bars be taken as the correct value, it was found that the deviation of the results of any one observer from this mean seldom exceeded 1 per cent. In one case it was as low as one hundredth of 1 per cent, and its mean value was somewhere about one-half of 1 per cent. Of course the different values of the modulus as obtained by the several observers do not vary wholly on account of the differences in the instruments used, but were also affected by errors in the measurements of the bars, errors of the testing machine, and personal errors of observation. There was, unfortunately, no attempt made to separate these errors from the purely instrumental ones. The results of the large number of tests thus carefully made do not appear to show that any one type of extensometer has a marked superiority over the others. Some of the results nearest to the mean were obtained by instruments of the simplest form.

CHAPTER IV.

TESTING OPERATIONS.—TENSION TESTS.

71.—The tests which have most frequently to be made in a testing machine are those in which the specimens are subjected to a tensile load or pull. A tensile test is easy to carry out, and the results are more readily comparable than in the case of tests of other kinds. Almost all the materials of construction may be readily

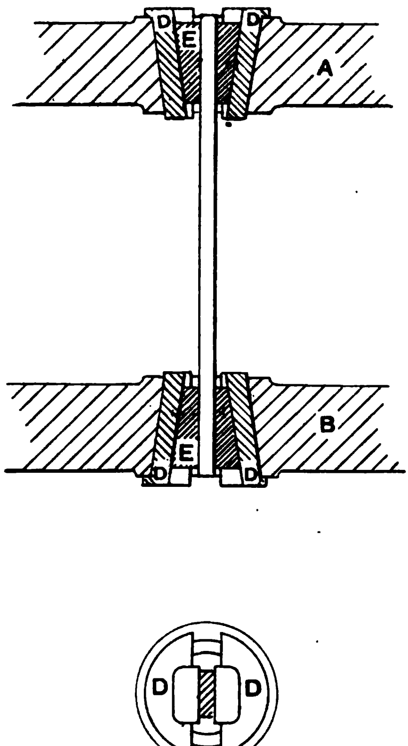


FIG. 55.

subjected to tensile tests: these include the metals, ductile and otherwise, timber, chains, hemp and wire ropes, and cement; the exceptions are brick, stone, concrete, and substances of like nature.

In the above description of testing machines, no particular mention has been made of the methods and appliances which are used for holding or gripping the ends of tension specimens. These will now be described.

72. Gripping Devices—For specimens of ductile substances such as wrought iron or steel or copper, whose ends have not been specially prepared for the purpose, hard steel wedges are employed for holding the ends in the testing machine. On Fig. 55 is shown a sketch of the gripping arrangement used in the Buckton-Wicksteed testing machines, for flat specimens. The grips

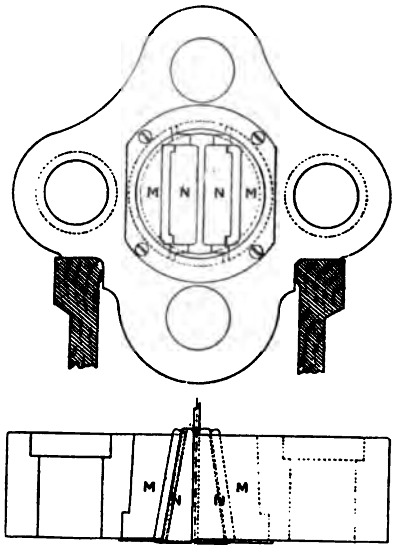


Fig. 56.

used on almost all other machines are similar in principle, with modifications in detail. In this figure, A and B are the two testing machine shackles, of which A is linked to the weighing beam and B to the ram of the straining cylinder. In the centre of each of these shackles is a conical hole, into which fit a pair of conical seating blocks D, D. These are made conical on the outside so as to fit the holes in the shackle, and have tapered recesses or grooves on the inside, in which rest the wedges themselves, E, E. These wedges are made smooth on the back and rough or serrated on the inside surface which comes against

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Iron and Steel Institute, 1888.

the specimen. Mr. Wicksteed forms his gripping surface by cutting the face of the wedge with shallow grooves, parallel and running along and across the face. These grooves leave large teeth or projections which penetrate the

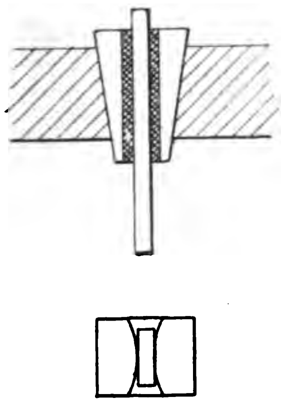


FIG. 57.

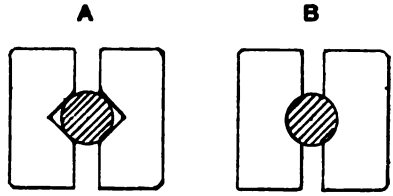


FIG. 58.

surface of the specimen to be gripped. Some makers prefer teeth of triangular section running only crosswise. For the rapid testing of not very heavy test pieces some engineers like to have the faces of the wedges coarsely file-cut.

a *b* *c*

FIG. 59.

The object aimed at in having the wedges resting in the conical bush is to allow the wedges to accommodate themselves to specimens which are not perfectly parallel,

and so prevent the gripping being all on one side. The same device is used in the Adamson machines. This is shown in Fig. 56. Here M, M, are the coned bushes, and N, N, the wedges. Messrs. Riehle attain the same object, which is really the preservation of the pull along the axis of the bar, by making the faces of the wedges convex in section, as shown on Fig. 57. For every machine a number of sets of double pairs of wedges must be kept, in order to accommodate test specimens of different thicknesses. Wedges of the shape shown in Fig. 55 are used for flat test pieces, generally those cut from plates. For round bars, wedges of the section

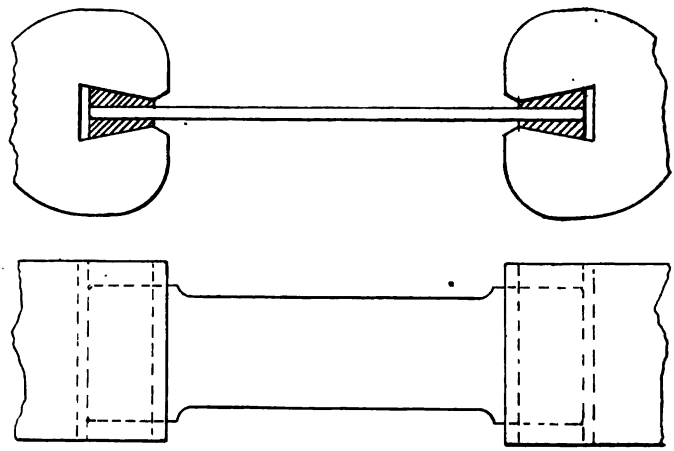


FIG. 60.*

shown on Fig. 58. (A), or sometimes of the section (B). Square bars may also be accommodated in the wedges marked A.

On Fig. 59 are shown photo views of the three types of wedges described.

In the Werder machine, shackles of the form shown on Fig. 60 are employed. By having the recess carried right through the shackle, plates of great width may be held.

A holding device, now hardly ever used, which was at one time the only one employed, was obtained by drilling two large holes in the ends of the bar, these ends being enlarged so as to allow of sufficient metal at the sides of the holes to secure ample strength for the ends: into these holes were inserted pins, which were themselves attached to the machine; in this way the whole force of the pull

* Unwin's "Testing," p. 177.

was transmitted to the test portion of the bar. So long as the holes were drilled in the true axis of the bar, this formed a good method of holding the specimens, but it was only applicable to flat bars cut from plates, and involved a waste of metal in order to form the enlarged ends.

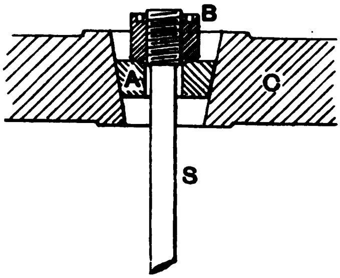


FIG. 61.

Many test bars are turned from the solid, and are provided with screwed ends. The typical way of holding these is shown on Fig. 61. Here the specimen is at S, the shackle is marked C. A taper bush A rests in the conical

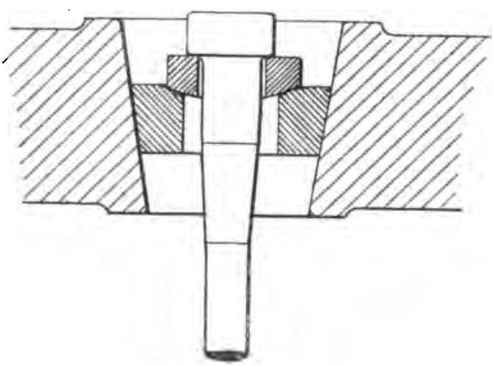


FIG. 62.

hole in the shackle, and serves to support a nut B, which is screwed on to the end of the specimen. The under part of the nut has a spherical form, and rests on a correspondingly spherical seating on the bush. By this arrangement the ends of the specimen are free to rotate to a small extent, and the bar can thus adjust itself so that the pull is along the axis, and there is no tendency to bending produced. This is especially important in the case of cast-iron

specimens, which are generally cast with a head upon each end. These heads rest upon bushes formed with spherical seatings, as shown on Fig. 62. These bushes have to be made in two halves, so that they can be placed in position over the head of the bar. The holding devices which have been described are the chief ones in use for tension specimens of the more ordinary materials; those used for timber, cement, chains, and ropes will be described later when dealing with these materials. On Fig. 63 is shown a section of the Maillard type of grip, which can be used for both cheese-headed specimens, and for those with screwed ends. It is especially useful when the specimens are very short. The holder is suspended from spherical seatings.

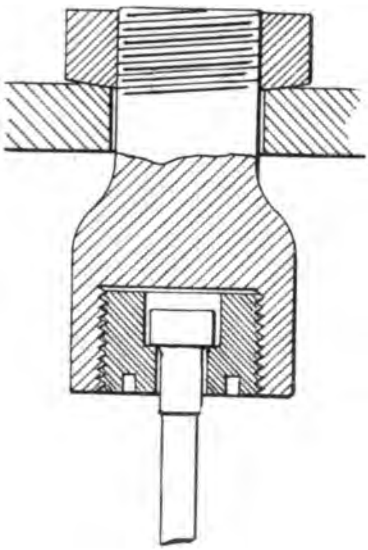


FIG. 63.

On Fig. 64 is shown the arrangement of gripping wedges for flat bars used on the testing machine at the Midland Locomotive Works. There it will be seen that the wedges are made with rounded backs so as to dispense with the use of conical seating bushes.

73. Forms of Specimens.—The form and dimensions which may be adopted for a test specimen are important in view of the fact that the shape of a bar has a very definite effect upon the results of the test. The forms which have been most generally adopted are shown on Fig. 65. Of these, A

is a specimen cut from a steel or iron plate, and provided with enlarged ends and pin holes for fixing in the machine; this form is practically obsolete. At B is shown a much more usual form; in fact, what may be called the standard form for plate specimens. Here a piece about 20 in. long and 2½ in. wide is cut from the plate; this is afterwards shaped in the manner shown, so as to leave about 12 in. between the shoulders, the narrow part being left about 1½ in. wide; there is thus left a clear length of 10 in. to be used for measuring purposes. 10 in. is the best length to be

Grips for Plate Specimens.

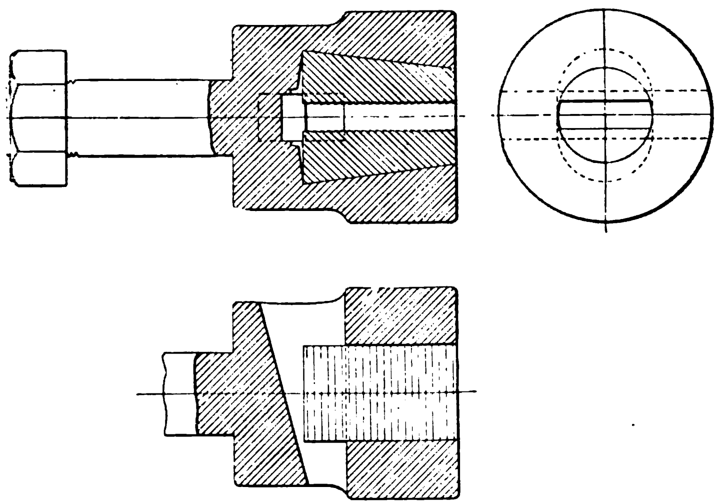


FIG. 64.*

employed, although other lengths are used by some experimenters. In making flat test bars of this kind it is most important to avoid sharp corners, where the shoulders are formed, and to have them rounded, as shown in the sketch. The shaping of the bars may be done in a shaping, milling, or planing machine. Where a large number of the same size have to be prepared at the same time, they can be put into a shaping machine, in a batch, and a cut taken right across them. A cheaper form than the last, and one more easily prepared, is shown at C. It is a plain parallel strip, with no reduction in the middle. The

* Inst. Mech. Eng., 1898.

objection to this form is that the fracture is liable to take place at a point not on the measured portion. In some cases, where the full quantity of metal is not available, much smaller specimens are employed, and the measurements taken on shorter lengths, but it is always advisable, where it can be done, to adhere to the 10 in. length, if only for the sake of uniformity. Bars are often tested with the skin on, the specimens being simply lengths of about 18 in., cut from the bar. This

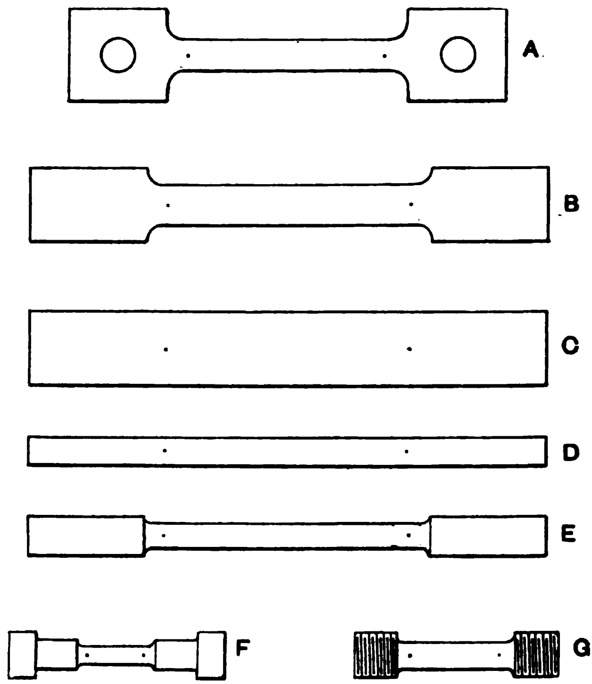


FIG. 65.

form is shown at D; here the measurements are taken on a 10 in. length, and about 4 in. are allowed at each end for gripping purposes. In some cases the better plan is adopted of taking a bar of the above length and turning it down in the middle portion, as shown at E, the ends being held in wedge grips; by adopting this plan the measuring portion is made perfectly uniform, and fracture necessarily takes place here. Smaller round specimens,

such as those cut from large masses of metal, are sometimes turned with enlarged ends, which are intended to fit specially shaped dies, or they are made with the ends screwed so as to fit a pair of screw dies. These two forms are shown respectively at F and G. Cast-iron specimens should be made with enlarged ends. These are the chief forms used for test specimens of ductile materials.

74. **Making a Tensile Test.**—It will now be well to describe in detail the several operations necessary in the carrying out of a simple tensile test, and for this purpose an example will be taken of the test of a round bar of mild steel, 18 in. long, 1 in. diameter. A full test will be discussed, that is to say, one in which all the available information is obtained.

75. **Preparing the Bar.**—After the bar has been cut to the required length, which should allow a clear length of ten inches for measuring purposes between the shackles, as well as sufficient length at the two ends for holding purposes, altogether about 18 inches, it should be marked off in inches from end to end, these inches being indicated by centre-punch marks. By thus marking the bar from end to end the extension on any length, including the point of fracture, whether the fracture has occurred in the part between the shackles, or, as sometimes happens, inside the wedges, can be readily measured. The inch division marks must be accurately set out, as upon these depends the accuracy of the measurements of extensions after fracture.

76. **Initial Dimensions of the Specimen.**—Before the specimen is put into the machine, or as soon as it is in place, its lateral dimensions must be ascertained; the longitudinal dimensions at the beginning of the test being determined by the centre-punch marks which have been placed on the bar. In the case of a round bar, it is the diameter that is required; when the bar is flat the width and thickness are to be measured. The lateral dimensions are rarely *quite* the same at every point throughout the length, and it is, therefore, necessary to take the measurements in several places and take an average. For making these measurements a vernier caliper, reading to a $\frac{1}{1000}$th of an inch, should be used.

77. **Balancing the Machine.**—Before finally tightening up the wedges, it is most important that the machine be care-

fully balanced and the vernier set to zero. That is to say, when the beam is in perfect balance, the reading of the machine should obviously be zero. It is necessary to draw special attention to this fact, because it is one that is often overlooked. Very frequently, when the machine has been altered for some other kind of test, additional tackle has been added to the weight on the upper shackle, and this throws the beam out of balance; in some cases the weight of the specimen itself may have a disturbing effect. It should, therefore, be taken as an axiom, that previous to every test the machine must be carefully inspected to make sure that it reads zero when there is no load on the bar. Another point which should be looked to before a test begins is to see that there is nothing to interfere with the free movement of the beam or beams; in some cases it may be found that the slides are tightened up too much, in which case there will be a certain amount of friction added to the load on the specimen, and which is not accounted for.

78. **Fixing the Specimen in the Testing Machine.**—This is an operation which, though simple, requires a considerable amount of care. In a vertical machine, the best plan is to fix the top end of the specimen first, and then get hold of the lower end and pull it tight by screwing down the lower cross-head by hand. Before using the wedge grips, care should be taken that both the socket and the wedges themselves are clean; otherwise there may be some trouble in getting the wedges out of their position after the completion of the test. A little oil rubbed over the wedges will do good in this direction. When the upper wedges have been placed in position, and the specimen inserted between them, care must be taken that the two wedges are on the same level, and that the specimen comes fully through them. To attach the lower end to the machine, the lower crosshead must be raised to the proper height by means of the hand screw adjustment, and the wedges then placed in position by inserting them with the two hands from the lower side. They will then have to be held in this position until a slight tension is put upon the specimen, so that the wedges are enabled to take a grip of the specimen. This pulling tight is effected by putting a small load, say, one-tenth of a ton, on the machine, and then tightening up by means of the screw gear. If there is any difficulty about the wedges gripping the bar, as is sometimes the case with hard metals, it will help matters and cause the teeth of the wedges to penetrate,

if the wider ends of the wedges are tapped with a hammer. When once the grips have taken hold and the test has begun, in most cases it will be found that they will retain their grip to the end. In horizontal machines there is less trouble, as a rule, chiefly on account of the fact that the wedges have no tendency to fall out of their places by their own weight. The specimen is now ready for testing.

79. Fixing the Extensometer.—If the modulus of elasticity is to be found, it will be necessary to attach the extensometer with which the elastic measurements are to be taken. When putting the bar in the machine, the centre-punch marks should be so placed that they can be easily seen and approached for purposes of measurement during the test. In the case of some extensometers, it will be necessary to provide two pairs of centre punch marks, ten inches apart, upon which to fix the instrument. Generally, however, in most modern extensometers, the attachment screws themselves penetrate the metal slightly, and so make their own marks. The extensometer should be applied to the bar, so that the gripping screws are opposite the axis of the specimen. There is no need to screw them up tight; it is quite sufficient if they are made to grip the bar lightly, so long as they are really firm and are not likely to slip. In some instruments an attachment is provided for holding the screw clips exactly ten inches apart, and perfectly rigid until the instrument is fixed upon the bar, when the clamp can be removed. This is the case with Professor Ewing's instrument, where a clamp or distance-piece holds the screw clips at exactly ten inches apart, and also maintains the gripping screws quite parallel. This is kept on until the instrument is in place, when it can be removed, leaving the extensometer in the proper position. By some such arrangement as this the instrument can be very quickly and accurately placed in position, and much time and trouble are saved.

The extensometer being now on the bar, the beam of the machine must be got into a floating position, with either no load on the specimen or a definite small load, say, a tenth of a ton. The latter arrangement is often convenient, especially on a vertical machine, where the wedges tend to become loose, and drop out of their places if there is no load on the bar. The pointer must now be set to zero, ready for the first reading.

80. Booking the Results.—In all testing operations it is most important that a careful and accurate system of book-

ing the observations be adhered to. If one measurement is missed, or incorrectly recorded, it may be that the whole of the work is wasted, and the test rendered useless. The measurements may be first recorded in a rough note-book, in pencil or ink, and afterwards copied into a book of a more permanent character, but great care should be taken that the original observations are carefully and systematically recorded.

In a tension test, such as the one we are considering, the information required is as follows:

PRELIMINARY INFORMATION—

Date.
Number of test.
Nature of material.
Special marks on bar (if any).
Original dimensions.

INFORMATION OBTAINED DURING THE TEST—

Loads.
Extensions resulting from these loads.
Permanent set (if any), after extensometer readings.
Load at which the elastic limit occurs.
Maximum load.
Breaking load.

81. Making the Test.—When the necessary preliminary information has been booked, and the extensometer finally adjusted, the test may proceed. As elastic readings have in this case to be taken, the load on the bar must be increased by small steps and the corresponding extension observed after each increment has been added. The magnitude of the increment will depend on the nature of the material and upon the size of the bar; it must be such as to give a clearly definite reading on the extensometer. In the present case an increment of one-quarter or half-a-ton will be suitable.

Great care must be taken that the readings observed on the extensometer be correct. The instrument should be carefully watched to see that there are no disturbing effects creeping in and that there are no backlash effects. Readings beyond the degree of accuracy which the instrument is capable of should never be attempted. This is a mistake that is often made.

If the modulus of elasticity is to be found with any degree of accuracy, it is necessary that the readings be

repeated once or several times. It is often found that the first set of readings are not as uniform as could be wished, and for this reason it is well to repeat the process. This is especially true in the case of observers who have not had a great deal of practice. In some cases it is necessary to take three, or even four, sets. Of course, it will be at once apparent that, if the elastic readings are to be repeated, the first loadings must not be up to the elastic limit. Generally speaking, the limit occurs after the bar has been stretched to about one-thousandth of its own length, so it is safe to go to this point without affecting the initial state of the bar. In the case we are considering the measured length is 10 inches, and one-thousandth of this is one-hundredth of an inch, so that the first set, or the two first sets, may be carried up to this point in the mild steel bar in question. This will be reached at a load of about twelve or thirteen tons. Supposing a third set to have been taken up to this point, and the readings are found to be satisfactory and regular, then the test must be continued by still applying increments of load and noting the corresponding extensions. As the limit is approached, it will be seen that the extensions per increment of load, which up to this point have been uniform, will begin to increase, and a point will be reached when these extensions become too great for the capacity of the extensometer. When this occurs the instrument must be removed from the specimen, and the extensions of the bar beyond this point measured by means of a pair of dividers and a steel rule divided into inches and decimals of an inch, up to hundredths. After each loading the dividers must be set to the distance between the 10 in. marks by applying them to the bar, and this distance measured by transferring the dividers to the rule. It will be found more accurate and convenient to apply the zero end of the dividers to one of the inch divisions of the rule rather than to one end.

As the loads get well beyond the elastic limit, it may be found convenient to make the increment greater; thus, the increments may be changed from quarter-tons to half-tons. Also, when the extensions become large, it will be found that the extension in each case does not occur at once, but that a little time must be allowed to elapse, during which the bar goes on stretching, before the measurement can be taken: that is to say, the bar must, as it were, be allowed to come to rest.

When the load has become large and the bar has stretched to a considerable extent, it will be seen that the scale of the metal—that is, if the bar has not been turned—begins to crack and peel off, and also the bar will be seen to visibly diminish in diameter, this diminution being at first uniformly distributed along the whole length of the bar.

When the maximum load is approached, however, the reduction of diameter begins to assume a maximum amount at one point of the bar. A distinct thinning takes place at this point, and the specimen appears to have a "waist." As this local contraction sets in, the load has probably reached its maximum amount, and it is soon found that the bar will no longer support the load which has caused this contraction. The explanation of this is simple. When local contraction begins to manifest itself, the area of the cross section of the bar begins to be more rapidly reduced, and, although the load may not be increased, the load per unit area rapidly becomes greater. This increase of load per unit area, or stress, has the immediate effect of still further increasing the local extension and contraction, and therefore the stress also. When this point is reached, the life of the bar is at an end, and fracture soon takes place by the tearing apart of the bar.

The local contraction only takes place in a marked degree in the case of the more ductile metals, such as mild steel, the better kinds of iron, copper, and metals of a similar nature. By careful manipulation it is possible, in the case of ductile metals, to ascertain both the maximum and the breaking loads. In order to do this, the maximum load is to be quickly noted, and then the jockey-weight rapidly run back towards zero until the load just balances the stress in the bar; by carefully adjusting the load in this way balance may be preserved until fracture takes place, and the actual breaking load obtained. In ductile materials this breaking load may be considerably below the maximum load.

Throughout the test, as the load is increased and the bar in consequence stretches, the weighing beam will fall from its horizontal position, and will have to be raised again, and balance preserved by the hydraulic appliances provided for taking up the strain of the specimen. In the case of the more ductile metals there will have to be quite a considerable interval of time between the increase of the load in each case and the measurement of the stretch, as a

little time is required for equilibrium to be attained. When the measurements are taken the beam should be floating freely in a horizontal position, and have no tendency to fall owing to a further stretching of the bar.

When the point of fracture has been reached and the bar broken in two pieces, the first thing to be done is to make sure that both the maximum and breaking loads have been properly noted. The broken bar can now be taken out of the machine, the load run back to its zero position, and the hydraulic ram allowed to return to its initial position by letting out the water which has been used to actuate it. The bar, having been taken out of the machine, can now be measured. The measurements required are: the diameter of the bar at the point of fracture, the distance between the two 10 in. marks on which the extensions have been measured, and also the distance between the pair of marks on each side of the actual fracture, which were originally two inches apart. These measurements can be made with an ordinary steel rule to the nearest hundredth of an inch. In some cases the fracture is found to have taken place outside the 10 in. gauge marks, and when this is so, another pair of marks must be selected so as to include the point of fracture. In measuring the diameter of the bar at the fracture, a vernier caliper may be used, but it is generally found that this diameter is not uniform and an average must be taken, depending upon the judgment of the experimenter himself. A note should be made in the book as to the nature and appearance of the fracture itself; thus, it may be defined as "silky," "crystalline," or "fibrous," as the case may be.

Having completed the test and obtained the above measurements, all the results can now be worked out and a diagram plotted. The following is an example of the record of such a test, the results of which are fully worked out in detail:

TEST RECORD.

Date: January 20th, 1899.

Specimen of: Mild steel. *Tested in:* Tension.

Original dimensions: 1·002 in. diameter. *Length:* 10 in. *Area:* 0·788 sq. in.

Final dimensions: 0·659 in. diameter. *Length:* 13·06 in. *Area:* 0·341 sq. in.

Load.	Extension.	Load.	Extension.	Load.	Extension.	REMARKS.
Tons.	Inches.	Tons.	Inches.	Tons.	Inches.	
0·5	0·0006	0·5	0·0005	11·0	0·0110	
1·0	0·0011	1·0	0·0011	11·5	0·0115	
1·5	0·0017	1·5	0·0016	12·0	0·0121	
2·0	0·0022	2·0	0·0021	12·5	0·0130	
2·5	0·0028	2·5	0·0026	13·0	0·050	Extensometer taken off at this point.
3·0	0·0033	3·0	0·0031	13·5	0·160	
3·5	0·0038	3·5	0·0036	14·0	0·210	
4·0	0·0044	4·0	0·0040	15·0	0·270	
4·5	0·0048	4·5	0·0045	16·0	0·340	
5·0	0·0053	5·0	0·0050	17·0	0·410	
5·5	0·0058	5·5	0·0055	18·0	0·510	
6·0	0·0063	6·0	0·0060	19·0	0·650	
6·5	0·0067	6·5	0·0065	20·0	0·870	
7·0	0·0071	7·0	0·0070	21·0	1·250	
7·5	0·0076	7·5	0·0075	21·9	......	Maximum Load.
8·0	0·0081	8·0	0·0080	18·4	......	Breaking Load.
8·5	0·0086	8·5	0·0085			Fine-grained silky fracture.
9·0	0·0091	9·0	0·0090			
Load taken off and the readings repeated.		9·5	0·0095			
		10·0	0·0100			
		10·5	0·0105			

Elastic limit: 13·00 tons. 16·50 tons per square inch.
Maximum load: 21·90 tons. 27·80 tons per square inch.
Extension per cent: On 10 in. = 30·6 ; on 2 in. = 55.
Reduction of area per cent: 56·5.
Modulus of elasticity: 28,800,000 lb. per square inch. 12·880 tons per square inch.

On this form are all the recorded facts taken note of during the test, and also the results which were calculated from the data so obtained.

The following are the details of the calculations involved. The calculation of the areas of cross-section need not be detailed here.

82. Stress at Elastic Limit.—The commercial elastic limit, or, as it is also called, the "yield point," is estimated from an inspection of the above figures, or better still, from the plotted diagram of the test. The load at the limit as here taken is that load which has just succeeded in producing an extension emphatically greater than the uniform elastic extensions which have been taking place regularly, or nearly so, up to this point. The increments of extension for equal increments of load near the limit were as follow:—

From 10·0 to 10·5	tons,	increment is	0·0005 in.
„ 10·5 to 11·0	„	„	0·0005 in.
„ 11·0 to 11·5	„	„	0·0005 in.
„ 11·5 to 12·0	„	„	0·0006 in.
„ 12·0 to 12·5	„	„	0·0009 in.
„ 12·5 to 13·0	„	„	0·0370 in.

At 12·0 tons the stretch begins to increase from 5 ten-thousandths of an inch to 6, and at 12·5 tons to 9, and then when 13·0 tons is reached there has been a sudden and vastly increased extension to 370 ten-thousandths.

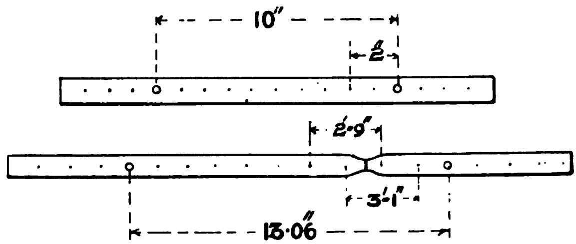


FIG. 66.

Between these last two loads the yield-point must be, and it is here taken as the load where the yield has really taken place. The true limit of elasticity is nearer 12·0 than 13·0 tons. It being then determined that the elastic limit has been reached at a *load* of 13 tons, the *stress* corresponding to this is:

Stress at Elastic Limit $= \dfrac{\text{load at elastic limit}}{\text{original area of the bar.}}$

$= \dfrac{13}{0\cdot788}$

$=$ **16·50** tons per sq. in.

83. Maximum Stress.—

The maximum stress $= \dfrac{\text{maximum load}}{\text{original area of the bar.}}$

$= \dfrac{21\cdot90}{0\cdot788} =$ **27·80** tons per sq. in.

84. Percentage Extension on 10 Inches.—After the completion of the test, the broken bar is taken out of the machine, the two halves placed together just as they have broken, and the distance between the two 10 in. gauge points measured. If the fracture has occurred *outside* these points, another pair of points, including the fracture, and which were originally 10 in. apart, must be selected.

In the present case this measured length is

13·06 in.

Therefore the extension is

$13\cdot06 - 10\cdot00 = 3\cdot06$. in.,

and the percentage elongation on the 10-in. length is:

Percentage Elongation on 10 Inches

$= \dfrac{\text{stretch}}{\text{original length}} \times 100$

$= \dfrac{3\cdot06}{10} \times 100$

$=$ **30·6** per cent.

85. Percentage Extension on 2 Inches.—This extension must be measured on a pair of gauge points originally 2 in. apart, and including the point of fracture. In the present case this was found to be 3·1 in; so that the actual extension on this length was

$3\cdot1 - 2 = 1\cdot1$ in.,

and

The Percentage Elongation on 2 Inches

$= \dfrac{\text{stretch}}{\text{original length}} \times 100$

$= \dfrac{1\cdot1}{2} \times 100$

$=$ **55** per cent.

On Fig. 66 are shown views of the bars both before and after testing. The measurements for obtaining the elongation are indicated.

86. Reduction of Area per Cent.—After the test the diameter of the bar at the point of fracture is measured, and the corresponding area of the cross-section at this point calculated. Then the required percentage reduction is:

Reduction of Area per Cent

$$= \frac{\text{original area} - \text{final area}}{\text{original area}} \times 100$$

$$= \frac{0{\cdot}788 - 0{\cdot}341}{0{\cdot}788} \times 100 = \frac{44{\cdot}7}{0{\cdot}788}$$

$$= \mathbf{56{\cdot}5} \text{ per cent.}$$

In a previous chapter* it has been shown that "so long as a bar remains parallel, and the volume is constant, the percentage of reduction of area, calculated on the original area, is always less than the percentage of elongation reckoned on the original length."

But this is not quite a case in point, because there is considerable local contraction, and the portion in question of the bar has not remained parallel, and, moreover, the local contraction is probably accompanied by a flow of metal into the 2-in. portion, causing the volume *not* to be constant.

87. The Modulus of Elasticity.—The first step in this calculation is the choosing of that set of elastic readings which is the most regular. In the two sets in question, if each reading be subtracted from that following it, the increments of length from ½ ton increase of load will be obtained. These are:—

Load. Tons.	First Set. Increments. Inches.	Second Set. Increments. Inches.
0·5	0·0006	0·0005
1·0	5	6
1·5	6	5
2·0	5	5
2·5	6	5
3·0	5	5
3·5	5	5
4·0	6	4
4·5	4	5
5·0	5	5
5·5	5	5
6·0	5	5
6·5	4	5
7·0	4	5
7·5	5	5
8·0	5	5
8·5	5	5
9·0	0·0005	0·0005

* p. 40.

On inspecting these two columns, it will be seen that the *second set* is the *more regular*, and probably the more accurate. It will, therefore, be well to neglect the first set and make use of the second.

We want the mean extension, say, per 1 ton of load. This can be found either, as above, by taking the mean of the $\frac{1}{2}$ ton extensions, and multiplying by 2. Thus, the mean extension per ton of load is

$$0{\cdot}0005 \times 2 = 0{\cdot}0010 \text{ in.};$$

or, better still, the method advocated by Dr. Kennedy can be used. In this the increments are reckoned on greater differences of load. In doing this, the greatest possible range should be taken. Thus, the extension at the load half way down the list should be subtracted from that at the last load, and so on, taking the successive pairs up the list. Suppose an interval of 4 tons be taken, the details of the process will be as follows:—

0·0090	0·0085	0·0080	0·0075	0·0070
0·0050	0·0045	0·0040	0·0036	0·0031
0·0040	0·0040	0·0040	0.0039	0·0039
0·0065	0·0060	0·0055	0·0050	0·0045
0·0026	0·0021	0·0016	0·0011	0·0005
0·0039	0·0039	0·0039	0·0039	0·0040

Take the mean of these—

$$\begin{array}{r} 0{\cdot}0040 \\ 40 \\ 40 \\ 39 \\ 39 \\ 39 \\ 39 \\ 39 \\ 39 \\ 0{\cdot}0040 \\ \hline 10\overline{)\,{\cdot}0394} \\ 0{\cdot}00394 \text{ in.}, \end{array}$$

and the extension per ton of load will be one-fourth of this; that is,

$$\frac{0{\cdot}00394}{4} = 0{\cdot}000985$$

which result is not quite the same as that first obtained. This will be taken as the correct result.

Now, the modulus of direct elasticity,

$$E = \frac{f_t L}{l}$$

where f_t is the stress producing the extension; L is the original length of the bar; and l is the extension corresponding to f_t.

Here

$$f_t = \frac{1}{0{\cdot}788} \text{ tons per sq. in.}$$
$$L = 10 \text{ in.}$$
$$l = 0{\cdot}000985 \text{ in.}$$

Therefore,

$$E = \frac{10}{0{\cdot}788 \times 0{\cdot}000985}$$
$$= \mathbf{13{,}880} \text{ tons per sq. in.}$$

Reduced to pounds per square inch, this value becomes **28,860,000.**

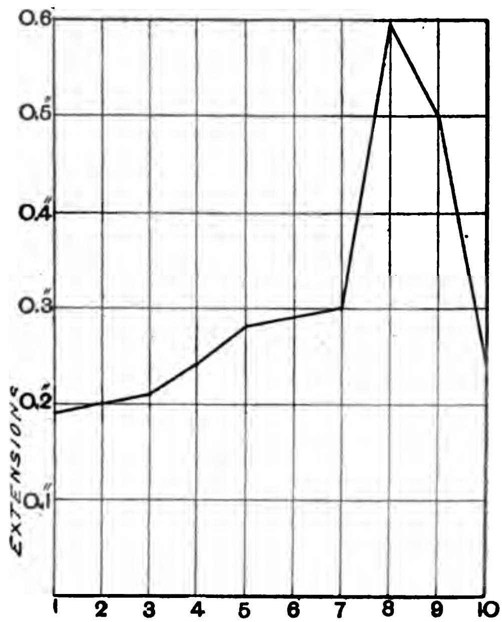


FIG. 67.

These results, both direct and calculated, are typical for specimens of ductile metals. They must not be taken so much as *results*, but rather as models of the methods of dealing with such tests.

88. Distribution of the Extension.—On Fig. 67 is a diagram showing the extension of each individual inch of

the ten inches between the two gauge marks. On this diagram, the numbers along the base represent the number of the inches from one end, and the vertical distances to the diagram represent the extension on these inches.

The actual figures are as follow :—

EXTENSION ON EACH INCH.

1st	0·19 inch.	
2nd	0·20 ,,	
3rd	0·21 ,,	
4th	0·24 ,,	
5th	0·28 ,,	
6th	0·29 ,,	
7th	0·30 ,,	
8th	0·60 ,,	The fracture occurred in this inch.
9th	0·50 ,,	
10th	0·25 ,,	
Making a total of	3·06 ,,	

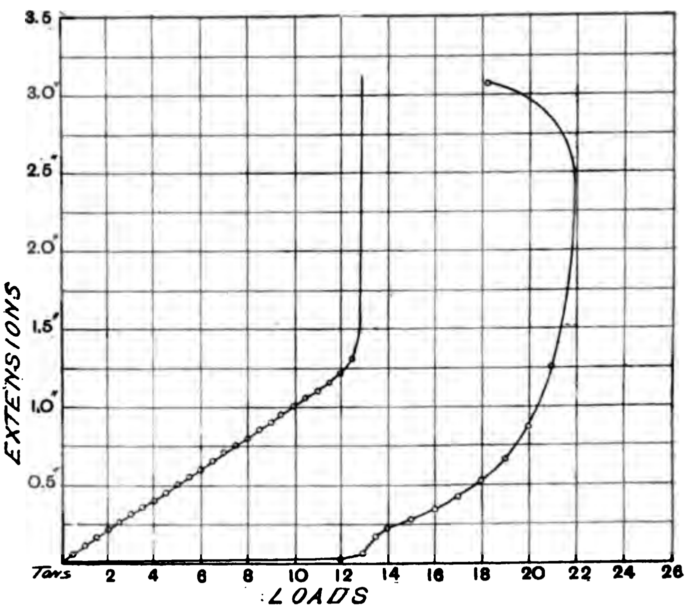


FIG. 68.

89. Plotting the Diagram.—It is often necessary and convenient to preserve a graphic record of a test, or, in other words, to plot a complete diagram of the test. In educational testing this should always be done. It gives the student an insight into the properties of the material he has tested, which cannot be obtained by a mere inspection

of figures. For the purpose of comparing tests of similar materials the use of diagrams is invaluable. In order to plot these diagrams, faint-ruled paper, divided into inches and tenths of an inch, should be used. For anyone to go through the process of measuring up a sheet of paper every time a diagram is to be plotted is wearisome in the extreme, and not at all necessary. On Fig. 68 are plotted two diagrams of the above test. The larger one on the right is a complete diagram of the test, and is called the *load-strain* diagram. The horizontal measurements represent loads as indicated by the scale; and extensions are plotted vertically to the scale shown. The first part of the diagram is approximately a straight line almost coinciding with the base line, and represents the period below the elastic limit when the extensions are relatively small, and can only be measured with an extensometer. After the load of 12 tons has been passed, the extensions, which up to now have been sensibly regular, begin to increase, and the line begins to curve upwards more and more rapidly as the load is increased. This rapid upward tendency ceases at 14 tons load, and the curve settles down to a uniform curve, the extensions increasing constantly.

The last measurement of extension, while the bar is in the machine, is made at a load of 21 tons. The *maximum load* is reached at 21·9 tons, and the specimen breaks at a lower load than this, namely, 18·4 tons. The last point on the curve, which here comes backwards, is at this load of 18·4 tons, the extension being the total elongation, 3·06 in., measured after fracture.

The second curve, to the left hand of the diagram, is the elastic portion of the above curve plotted to a much larger vertical scale, 100 times the first. It will be seen that this is an almost straight line for the greater portion, and curving very rapidly upwards after a load of 12 tons has been passed. This load of 12 tons represents the true elastic limit, the commercial limit being taken at 13 tons, after a distinct set has taken place.

In the curves shown on Fig. 68 the actual points plotted are represented by the centres of small circles, and a smooth curve has been drawn through these.

90. Remarks on Tension Testing in General.—The case which has just been described in detail may be taken as being typical of most tension tests. The tests of other materials, and of specimens of other shapes, are similar in

a general way, with small differences in detail. It will be useful to note any modifications which are required.

In the first place, it may be pointed out that *all* the measurements and results which have been enumerated are seldom required, especially in ordinary commercial tests. In tests of this kind the quantities to be determined are usually as follow:—

The maximum stress.
The stress at the elastic limit.
The extension on 10 in. of length.
The extension on the 2 in., including the point of fracture.
The reduction in area per cent.

Sometimes certain of these are omitted. The modulus of elasticity is not often required for commercial purposes. Its determination is most useful practice for engineering students, besides helping them to a knowledge of the elastic properties such as cannot be obtained in any other way. As regards the effect of the material itself on the mode of carrying out the test and on the subsequent calculations, these will now be referred to in detail.

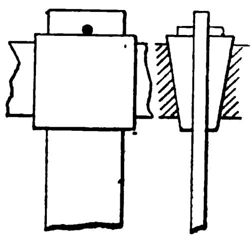


Fig. 69.

91. Mild Steel, High-grade Wrought Iron, Copper.— The treatment of these three in tension testing operations is pretty much the same. They can all be held satisfactorily in wedge grips, although in some cases the specimens are turned and chased to fit screw dies. In testing strips of plate a difficulty is sometimes found in getting the teeth of the wedges to bite at first, especially if the metal is a little harder than usual. In cases such as these the holding of the wedges is greatly helped by drilling small holes through the specimen close to the ends, and inserting short pins in these holes. These pins may be about $\frac{1}{4}$ in. diameter.

They will be found to prevent the specimen from being pulled through the wedges in the first instance, and in this way help them to take hold of the bar. This arrangement is shown on Fig. 69. In the three metals which have been mentioned, as the metal is very ductile, the percentages of extension and of reduction in area are large. In these metals also the bar is often found to break at a load less than the maximum load, as it is generally possible, when local contraction is observed to be setting in, to run back the load to such an extent as to balance the pull on the specimen, and to continue diminishing the load until fracture takes place.

92. Low-grade Wrought Iron, the Harder Kinds of Steel, Gun-metal, and Brass.—These may be taken as representative of the less ductile metals. They are certainly ductile, but to a smaller extent than in those already mentioned. The holding is effected both by wedge grips and screw dies. The extension and the reduction of area are less than in the former cases, but are still considerable. In these metals, fracture generally takes place at, or very near, the maximum load.

93. The Commercial Elastic Limit.—The best way to obtain the actual elastic limit with accuracy is to take careful measurements with an extensometer, plot a diagram to a large vertical scale, and notice where the curvature begins. An inspection of the figures will also give it.

The commercial limit, called also the "yield point" and the "breaking down point," is best obtained with certainty by setting a pair of dividers to as great a length as is possible on the bar. One point is then held on the lower gauge point, and the other point is made to scribe an arc on the upper surface of the bar. When the bar has definitely passed the limit the scribed line very perceptibly and rapidly thickens. Some observers depend upon carefully watching the end of the weighing beam, which begins to drop rapidly when the limit is reached. This is not advisable, as it is not at all certain, and a considerable error may be made by an unpractised observer.

COMPRESSION TESTS.

94. When a material is to be tested in compression there are certain rules as to proportions and methods of holding which it is important to observe. If the specimen is very short in proportion to its thickness, failure

will take place by crushing alone; if, on the other hand, the length is great relatively, failure will take place by bending or buckling; a length midway between

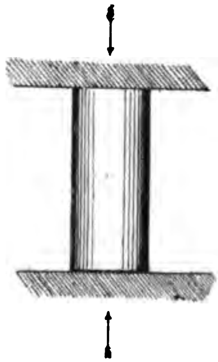


FIG. 70.

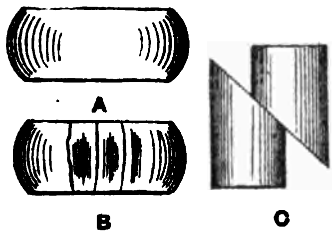


FIG. 71.

these will result in the specimen collapsing, partly by reason of its material being crushed and partly by bending. In a compression test, unless it is otherwise specified, it is supposed that failure only takes place by simple crushing, and therefore it is necessary that the specimen for this purpose shall be short. Metal compression specimens are generally turned in a lathe, and should be not more than two or three times their diameter in length. Such a specimen is shown on Fig. 70. The ends of short compression specimens must be truly at right angles to their axes and quite plane. This is most important, and it is better to have the ends very slightly hollow than rounded. The plates of the testing machine, between which the specimen is to be crushed, should be perfectly flat and free from lumps or unevennesses: the surfaces of these plates must be at right angles to the direction of the thrust. The reason of all these points is obvious. A tension specimen will tend to straighten and accommodate itself to the direction of the pull if this is initially a little out of centre. In a compression test the case is different. If there is a slight bending or want of truth at the beginning, the effect of the load will be to increase and accentuate this instead of diminishing it; so that great care must be taken that the load shall be transmitted truly along the axis of the bar; otherwise the result of the test will be greatly modified.

In the case of some of the softer materials it is usual and necessary to insert a bedding substance between the specimen and the compression plates, so as to distribute the load uniformly, just as mortar is used in masonry construction. But this is not necessary in the case of the metals, and it is sufficient to place the specimen between a pair of hard, true plates.

A reference to Fig. 25, page 67, will make clear the arrangement which is made use of for carrying out compression tests on a vertical Buckton-Wicksteed machine. Here the lower compression plate B is slung from the upper tension shackle A, and the specimen to be crushed is placed between this plate and the crosshead C, which is attached to the ram. A somewhat similar arrangement is made use of in most of the other machines.

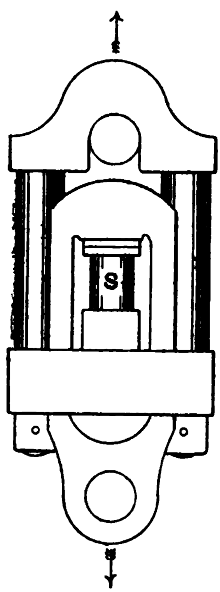


FIG. 72.

A form of compression gear, adapted for machines which are primarily arranged for testing in tension only, is shown in the accompanying figure.* This form of shackle has been designed and used by Professor Unwin, and consists, as will be seen, of a pair of stirrups fitting into one another, and which can be pulled apart by being attached to the tension shackles of the machine. The specimen is marked S. The top seating against which the specimen rests is made with a spherical joint, so that the pressure is applied directly in the line of pull.

Reference should also be made to Figs. 26, 27, 31, 34, 35, and 38. The four-pillar machine of Fig. 27 possesses advantages over other machines of the vertical type, for compression, from the fact that it is provided with means whereby the thrust blocks can be truly guided along the four pillar slides.

The strains of a short compression specimen are not so easy to determine as in the case of a longer tension specimen. Where the modulus of elasticity in compression is required, it is better to make use of a specimen of rather greater length than ten inches, and to use an ordinary

* Unwin's "Testing," p. 185.

extensometer, care being taken that the diameter of the bar is sufficient to render unlikely any possibility of buckling.

The elastic deformations of short compression specimens have not often been measured. An instrument for this purpose, designed and used by Professor Unwin, is shown

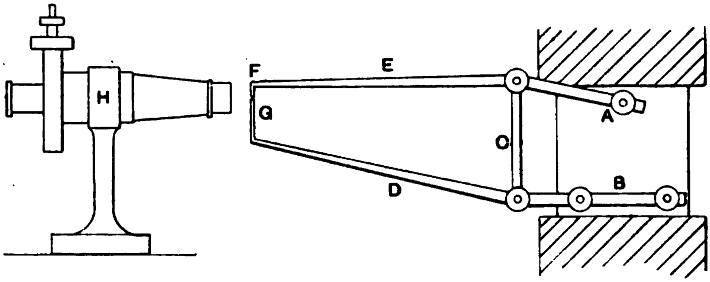


Fig. 73.

on Fig. 73. This was primarily designed for measuring the elastic compressions of small blocks of stone, concrete, or similar substance, but there is no doubt that it could be used for similar purposes on metal compression pieces, or the same principle might be made use of with small differences in detail. The working of this instrument will be appreciated by reference to the figure. The lower clip B is held to the specimen by means of four set screws, and the upper one clips the block by means of one pair of screws. These two clips have prolongations, D and E respectively. There is a vertical pillar C, which carries the knife edge about which the upper clip rotates. As the block is compressed, and the clip A descends with respect to B, the point of this upper clip F rises with respect to the end of the lower clip G, and this movement is two and a half times the compression of the block. On these ends are two fine lines drawn upon silver, and their relative distance is measured by means of a micrometer microscope H.

Readings to from $\frac{1}{20000}$ to $\frac{1}{50000}$ of an inch can be taken.*

In most cases, however, it is only the semi-plastic strains that are measured. In the case of a tension test, the extent to which the loads can be increased is limited by the point of fracture occurring, when the test is at an

* Unwin's "Testing," p. 225.

end. But in the compression tests of many of the metals, it is possible to go on increasing the loads almost indefinitely. When carrying out a compression test, the measurement of the strains, beyond the elastic limit, can be made in one of two ways. The most accurate plan is to release the load after each increment has been imposed, take the bar out of the machine, and measure its length with a pair of vernier calipers. After this the bar is put back and the test proceeded with.

Another and quicker way is to measure the distance between the compression blocks after each increment of load, and assume this distance to be the same as the length of the specimen. If the plates are true, and the measurements are always taken in the same place, this method is sufficiently near for ordinary purposes. In taking the measurements a pair of inside calipers and a rule may be used. Better than this is an inside micrometer caliper.

The behaviour of short compression specimens of the various metals is very different. Annealed copper is one of those which display properties of almost perfect plasticity. As the load is increased the specimen diminishes in length and increases in its lateral dimensions; for a time the true cylindrical form is maintained, but later on the specimen assumes a more barrel-shaped form, the greatest increase in diameter taking place in the middle and diminishing towards the two ends. This is probably assisted by the friction between the specimen and the compression blocks. Mild steel behaves in very much the same way, though if the load is carried beyond a certain point, the edges of the disc will begin to show signs of cracking. Wrought iron also can be compressed almost indefinitely, but cracks begin to show at lower loads than in the case of mild steel, and this is more especially true of the poorer brands. Brass and gun metal show less plasticity than those mentioned above. In some cases they may be compressed until they finally crumble into small pieces; in others they fail at an earlier load by violent and sudden rupture, fracture taking place by shearing across a plane forming an angle of about 45 deg. with the axis. Of course, it will readily be understood that there is a great difference between brass and gun-metal specimens made from different mixtures. Cast iron always fails by sudden rupture across a plane forming an angle of 45 deg. with the axis of the specimen. The rupture is accompanied by a loud report, and the several pieces of the specimen fly outwards with

great force, so that it is necessary, for the safety of the operator, to surround the bar with wood or sacking, which will prevent the pieces from being shot outwards. The compressive strain of cast iron is small, and measurements are not usually taken Aluminium shows a considerable amount of plasticity, but cracks under a high load.

EXAMPLE OF COMPRESSION TEST.

Date: January 21st, 1899.
Specimen of: Copper.
Tested in: Compression.
Original dimensions: { 0·95 in. dia. 2·5 in. long. 0·708 sq. in., original area.

Load.	Length.	Compression.	Remarks.
Tons.	Inches.	Inches.	
3	2·49	0·01	
4	2·47	0·03	
5	2·45	0·05	
6	2·42	0·08	
7	2·38	0·12	
8	2·34	0·16	
9	2·30	0·20	
10	2·27	0·23	
12	2·18	0·32	
14	2·09	0·41	
16	2·00	0·50	
18	1·89	0·61	
20	1·80	0·70	
25	1·54	0·96	
30	1·33	1·17	
35	1·17	1·33	
40	1·05	1·45	
45	0·95	1·55	The load was taken off at 50 tons load. No sign of cracking.
50	0·88	1·62	

95. **The Compression Diagram.**—On Fig. 74 is shown a diagram which has been plotted from the results of the test quoted above. Here, as before, loads are plotted horizontally and lengths upwards, or, in other words, compressions downwards.

In a compression test the main object is to determine the load at which the elastic limit is reached, because after this point has been passed very little further information

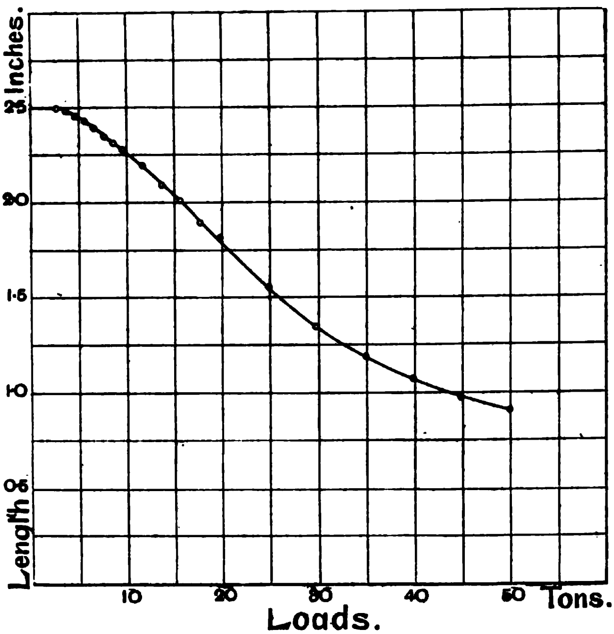


FIG. 74.

can be obtained from the test. In a tension test the case is different. Here many facts relating to the nature and properties of the material are revealed when the specimen is tested to destruction, and measurements of the final dimensions are made. The curve on Fig. 74 shows distinctly that a very well marked plastic deformation takes place after a certain load had been reached. Beyond this point the curve is very regular and uniform. Before this is reached the curve is almost flat, but it begins to fall away after the elastic limit has been passed.

The appearance of three typical compression specimens after sustaining a high load are shown in Fig. 71. Here A represents the appearance of a plastic substance, such as mild steel or copper, after compression; B indicates the appearance of a piece of a metal which has a tendency

towards lamination, such as wrought iron; and C shows how a hard, brittle metal like cast iron, fails by the sliding or shearing across a plane inclined to the axis at an angle of about 45 deg. It must, of course, be understood that the fracture is not nearly so clean and regular as that shown, but it approximates to this form.

96. Real Stress-strain Diagrams.—Two diagrams have been shown on Figs. 68 and 74, one being what is generally called the "stress-strain" diagram for a specimen of mild steel tested in tension, and the other a similar curve

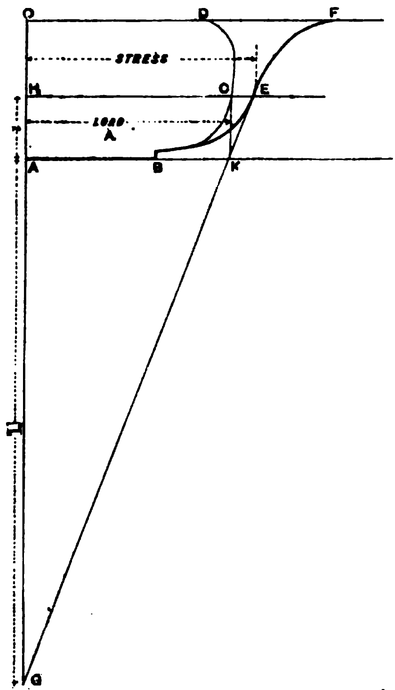


FIG. 75.

for copper tested in compression. The term "stress-strain" as applied to these diagrams is not the correct one. It would be more appropriate to call them "load-strain" diagrams. Loads are plotted horizontally and the corresponding strains vertically. If the stresses were at all times proportional to the loads, in a constant ratio, the curves would be converted into "stress-strain" diagrams by a

simple change of scale. But this is not so. If the specimen is at all ductile, longitudinal strains beyond the elastic limit are accompanied by corresponding alterations in the lateral dimensions, and as the length increases, the area of the cross-section diminishes, and the contrary takes place when the length is diminished, as in a compression specimen. Within the elastic limit the stress on the bar is sensibly proportional to the load, but when this point is passed, the stress varies at a rate different from that of the load. In a tension test the area of the cross section diminishes as the load increases, and as the stress at any point is the load divided by the area, the stress per unit area increases more rapidly than the load. Hence in this case the load is not itself a measure of the stress.

A true stress-strain curve could be obtained by measuring the lateral dimensions of the bar at each increase of load, calculating the areas at these points, and dividing the load by the area in each case to obtain the stress, and plotting the diagram from these results. Such a plan, however, would be extremely laborious. The same end can be gained by first plotting the load-strain diagram, and by means of a simple geometrical construction, obtaining the true stress-strain curve from this.

The determination of this curve for a tension test of mild steel is shown on Fig. 75. Here the load-strain diagram A B C D is plotted as before. Then the line O A, at the extreme left of the diagram, from which the loads have been measured, is produced to G, A G being made equal to the length of the specimen previous to the test, O A being the extended length. Both these must be to the same scale. Take any point on the load-strain curve C, and draw through it a horizontal line C H. Also draw a vertical through this same point to meet the base line in a point K. Join G and K, and produce this to cut the line H C produced in E. Then E will be a point on the real stress diagram.

The proof of this depends on the assumptions that the bar remains parallel during the plastic deformation, and also that the volume of the bar remains constant. These are both approximately true.

Let A = the area of the original cross-section of the bar.
,, a = the cross-section at the load H C.
,, $L = GA$ = the original length.
,, $l = HA$ = the extension corresponding to the load H C.

Then the original volume of the bar is

$$= A \times L, \text{ and}$$

the volume at the point in question is

$$= a \times (L + l).$$

But these are assumed to be equal, so that

$$A L = a (L + l),$$

or

$$\frac{a}{A} = \frac{L}{L+l}$$

$$= \frac{G A}{G H}$$

$$= \frac{A K}{H E}, \text{ by similar triangles}$$

Again, the apparent stress is $\frac{\text{Load}}{A}$; and the real stress is $\frac{\text{Load}}{a}$. So that

$$\frac{\text{Apparent stress}}{\text{Real stress}} = \frac{a}{A} = \frac{A K}{H E}$$

Therefore, if, in the diagram, A K or H C represents the *apparent stress* or the $\frac{\text{Load}}{\text{Original area}}$, the distance HE, obtained by the above construction, will represent the *real stress*, or the $\frac{\text{Load}}{\text{Present area}}$. In the same manner, a number of other points can be found on the real stress-strain curves. When the maximum load has been passed, local contraction sets in, and the construction is no longer applicable. The last point, F, on the real stress curve must be obtained by dividing the final load by the final area, as obtained from the broken specimen. Thus,

$$\text{Final stress} = O F = \frac{\text{Breaking load}}{\text{Final area}}.$$

This value must be plotted on the diagram and a smooth curve drawn through all the points obtained. A B E F is then the real stress-strain curve.

A similar construction may be applied to compression

curves. An example of this is given on Fig. 76. The construction will be clear from the diagram.

Here

L = the original length of the specimen.

l = the compression or shortening.

A = the original area.

a = the area at the point in question.

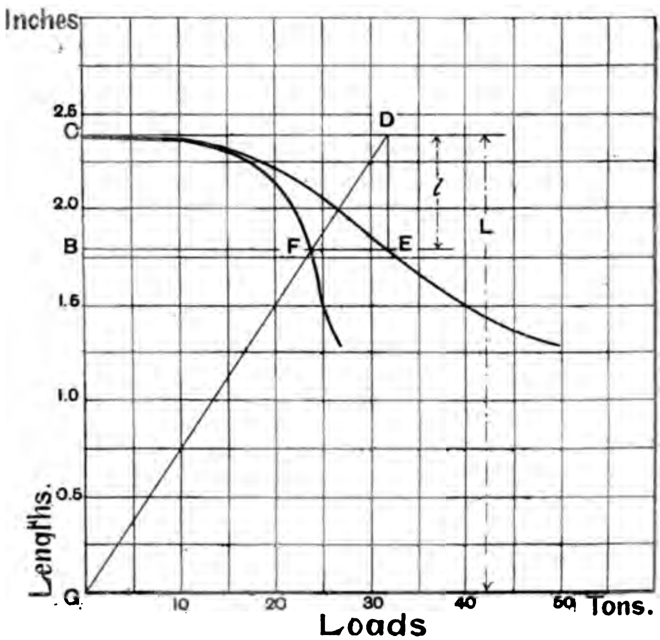


FIG. 76.

The volume being supposed to be constant, and the specimen to have kept its parallel shape,

$$A \times L = a \times (L - l)$$

$$\frac{A}{a} = \frac{L - l}{L}$$

$$= \frac{GB}{GC}$$

But

$$\frac{\text{Real stress}}{\text{Apparent stress}} = \frac{\frac{\text{load.}}{a}}{\frac{\text{load.}}{\text{A}}}$$

$$= \frac{\text{A}}{a}$$

$$= \frac{\text{G B}}{\text{G C}}$$

$$= \frac{\text{B F}}{\text{B E}}.$$

The defect in using this construction is due to the fact that, after the first few loads beyond the elastic limit have been passed, the parallel form leaves the specimen, and it becomes more and more barrel-shaped.

Chapter V.

TESTING OPERATIONS.—*(Continued.)*

SHEARING AND BENDING TESTS.

97. Shearing Tests.—There are fewer tests in compression than in tension, and there are still fewer in shear. The reason for this is not far to seek. Shearing tests are not so easy to carry out satisfactorily as are tension tests, strain measurements are difficult to make, and, moreover, these tests yield no results beyond the ultimate shearing stress. If the tensile properties of a metal are known, or can be ascertained, it is sufficient for all practical purposes to assume the shearing strength to bear a definite ratio to the tensile strength, as it has been determined that this shearing strength does depend on the tensile strength in a fairly constant ratio for a given metal. What has here been said relates only to direct shearing tests where the conditions that obtain are similar to those in a riveted joint. Shearing takes place in a bending test, but the most satisfactory way of investigating the shearing properties of a material is by subjecting it to a test under a torsional stress, where there is shear taking place in a circular direction.

A reference to Fig. 5 (p. 16) will make clear the conditions under which a shearing test is to be carried out. If the bar to be tested is A B, the portion A must be rigidly held while the other part B is also held in a similar way; but these two portions, A and B, are to be moved in opposite directions. It is extremely important that the two holders or shackles shall be placed very close together, so that there is no tendency to bending in the portion between the two in which the shear takes place. This is effected by having the two shackles placed very near to one another, and by making them to fit the bar accurately and tightly, so that there is no play or freedom to yield. In some shearing tests, single shear, as depicted in Fig. 5, is made use of. It has, however, been found much more convenient to apply the load in double shear; that is to say, to have the two end portions of a bar held, and to shear away the middle portion.

98. Shackles for Holding Shearing Specimens.—Shearing specimens may be either round or square or flat. A very convenient form of shackle for holding round turned

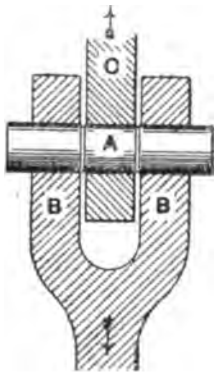


FIG. 77.

specimens is shown in Fig. 77. Here the specimen to be tested in shear is marked A. The specimen in this case is a round one, and is turned so as to fit the shackles accurately. The shackles themselves are B B and C. Of these C fits the middle portion of the bar, and is attached to one of the tension shackles of the testing machine, so as to be pulled in the direction shown by the arrow; the two outer portions of the piece are held in the other shackle, marked B. This is attached to the other tension shackle, so that it can be pulled in the opposite direction from that of the first. In shackles of this form it is most important that the bar be fitted tightly into the holders, so that it cannot possibly be bent and caused to fail in that way. The reliability of the results of a shearing test depend, to a great extent, on the manner in which the test piece is gripped. It is usual in this arrangement of a shearing test to slightly nick the bar in the parts where failure may be expected to take place. These grooves are shown on the figure. The holders themselves must be of hardened steel.

In one form the cutting edge of the middle holder is adjustable on a spherical joint, so that the pressures on its two edges may be equal.

This form of shearing tackle gives good results for the more ductile metals, but where cast iron is to be dealt with a modified form must be employed, as there is too great a

possibility of cross-breaking. The shearing test apparatus shown in Fig. 78, as used by Professor Johnson, of Washington University, is suitable for all classes of metals. Instead of the test piece being simply placed in position in the shackes it is firmly bolted in place, as shown in the illustration. The holding dies are made of hardened steel. Both the middle and ends are fixed in this way. The load is applied by placing the apparatus between the two compression plates of a testing machine. There is no reason why this should not be arranged so that the load is applied from the tension shackles as before. The bar to

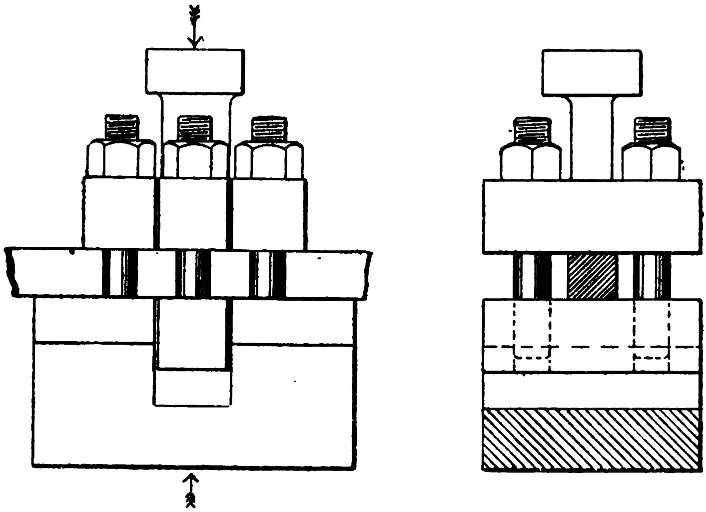


Fig. 78.*

be tested may be of the square form, as shown, or the dies may be cut out in the form of semi-circular recesses to take round bars. In this apparatus it will be seen that there is no possibility of freedom or shake, and consequently no tendency to cross-breaking.

It is not usual when using this apparatus to cut grooves in the bars.

The operation of carrying out a shearing test is fairly simple in the case of the first piece of apparatus described; care must be taken that the test bar fits the holders accurately and tightly, and also that the pull is quite central and symmetrical. Before the test, the dimensions of the bar must be carefully determined. In this case the

* Johnson's "Materials of Construction," page 387.

required dimension will be the diameter at the bottom of the grooves where failure may be expected to take place. When the bar has been placed in the machine it is only necessary to increase the load until failure takes place. This applies to both kinds of holding apparatus. Only in very few cases has an attempt been made to measure the strains in a bar under direct shear. Mr. Andrew Kirkaldy has measured the amount the dies have moved relatively to one another before actual shear had taken place, which strain he has called the "detrusion." This he found to be a sensibly constant quantity for the same metal.

The following are two examples of shearing tests, one of a bar of mild steel and the other of cast-iron. The data obtained from the test and the calculated results are both given; it will also be seen that the tensile strength of the same material is given, and the ratio which the shearing strength, in tons per square inch of total section, bears to the tensile strength is calculated also.

SHEARING TESTS.

Material.	Diameters at the two sections. Inches.		Areas in square inches.		Total Area sq. ins.	Shearing load. Tons	Shearing stress f_s Tons per sq. in.	Tensile stress f_t Tons per sq. in.	$\frac{f_s}{f_t}$
Mild Steel	0·803	0·807	0·507	0·511	1·018	22·91	22·50	25·95	0·87
Cast Iron	0·816	0·824	0·522	0·532	1·054	10·05	9·54	9·74	0·98

These figures hardly require any explanation. In both cases the bars were tested in double shear, and the total area is taken as the sum of the two individual areas through which shearing has taken place. The shearing load is the actual load required to cause the bar to be completely severed in three pieces. The ratio of the shearing to the tensile stress should always be ascertained where possible. This value is found to vary somewhat in the different metals. Generally speaking this ratio is higher the lower the tensile strength. In the following table are quoted a few typical examples of the results of shearing tests, as given by different authorities.

TABLE OF SHEARING STRENGTH OF VARIOUS METALS.

Material.	f_s Shearing strength. Tons per sq. in.	f_t Tensile strength. Tons per sq. in.	Ratio. $\frac{f_s}{f_t}$	Authority.
Bessemer Steel	35·21	52·20	0·67	Platt and Hayward
Crucible Steel	33·30	52·16	0·64	Platt and Hayward
Steel Propeller Shaft	18·12	27·36	0·66	Kirkaldy
Cast Steel	27·60	28·04	0·72	Platt and Hayward
Landore Rivet Steel	23·00	28·40	0·81	Platt and Hayward
Siemens-Martin Steel	21·05	25·75	0·82	Platt and Hayward
Rivet Steel	24·35	27·46	0·88	Kennedy
S. C. Crown, W. I.	20·72	24·56	0·85	Platt and Hayward
Netherton Crown Rivet Iron	21·21	25·01	0·85	Platt and Hayward
W. I. Bars	20·37	23·44	0·87	Popplewell and Coker
Copper	11·60	14·00	0·83	
Muntz Metal	18·60	25·46	0·73	Platt and Hayward
Gun Metal	12·47	13·68	0·91	Platt and Hayward
Hard Rolled Bronze	16·06	26·90	0·59	Kirkaldy
Bronze Castings	10·39	11·48	0·90	Kirkaldy
Cast Iron	9·54	9·74	0·98	Popplewell and Coker

99. **Punching Tests.**—These are analogous to shearing tests; in fact, punching is in reality shearing on a cylindrical instead of a plane surface. These tests may easily be carried out in an ordinary testing machine which has been arranged for compression tests. The only additional apparatus required is shown on Fig. 79. Here A is the punch, made slightly tapering upwards, B is the plate to be punched, and C is the lower die or bolster, in which is a conical hole D. The smaller diameter of this hole is made slightly larger than the bottom diameter of the punch, so that there may be sufficient clearance. In using

these in a testing machine the punch is fixed to the upper compression plate, and the bolster to the lower one. The piece punched out is slightly conical in shape, but it is usual to take the diameter of the circle upon which the shear takes place as that of the cutting edge of the punch. The operation itself is simple. It is only necessary to

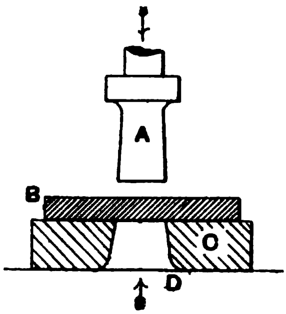


FIG. 79.

place the specimen beneath the punch upon the bolster, and then to bring the two together and increase the load until the failure has taken place by the punch shearing the piece out of the plate. The following is an example of such a test. In this case the tensile strength of the same plate has been previously ascertained.

PUNCHING TEST.

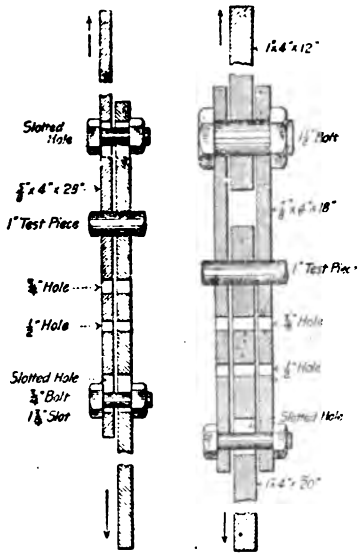
Material.	Thickness, inches.	Diameter of punch, inches.	Punching load, tons.	f_s Shearing stress, tons per sq. in	f_t Tensile stress, tons per sq. in	$\frac{f_s}{f_t}$
Mild steel.	0·39	1·00	32·00	26·20	31·10	0·84

The shearing area is

$$a = \text{diameter of punch} \times 3{\cdot}141 \times \text{thickness of plate}$$
$$= 1 \times 3{\cdot}141 \times 0{\cdot}39.$$
$$= 1{\cdot}22 \text{ sq. in.}$$

$$\text{The shearing stress} = \frac{\text{Punching load}}{a}$$
$$= \frac{32}{1{\cdot}22} = 26{\cdot}20 \text{ tons per sq. in.}$$

100.*Shearing Tests by Professor Talbot.—Some recent shearing tests, made by Professor Talbot, of Illinois, are interesting, both as regards his methods and the results obtained. The specimens tested were subjected to both single and double shear. The apparatus used is shown on Fig. 80. That marked *a* is for single shear tests, and consists, as will be seen, of two plates of steel caused to slide close to one another by means of a pair of bolts working



a FIG. 80. *b*

in slotted holes. Pairs of holes are provided for taking in 1 in., ¾ in., and ½ in. test pieces. The loads are applied in a tension testing machine. A similar piece of apparatus is used for double shear, as shown at *b*. These test plates were of tool steel of 35 tons per square inch tensile strength. The testing machine used was one by Olsen. It was found that little perceptible distortion took place in the holes of the test plates.

The following table gives the principal results of shearing tests made upon rivet material, of which the tensile strength was also determined.

The figures given in the table are taken from the actual published results, but are here given in tons instead

* See "Mechanical Engineer," Sept. 3rd, 1898.

of pounds. It will be noticed that the ratios obtained are somewhat lower than the one which is often quoted, namely 0·80, being most frequently in the neighbourhood of 0·75. At the same time this ratio is variable over a limited range. It will be noticed that for each metal, bars of smaller diameter give the larger ratios. This result is curious and cannot be accounted for by the bending

TABLE.—COMPARISON OF SHEARING AND TENSILE STRENGTHS OF RIVET MATERIAL.

Diameter. Inches.	Tension. Ultimate Strength. Tons per square inch.	Single Shear. Ultimate Strength. Tons per square inch.	Single Shear. Ratio of Shear to Tension. Per cent.	Double Shear. Ultimate Strength. Tons per square inch.	Double Shear. Ratio of Shear to Tension. Per cent.
	VICTOR BOILER RIVET STEEL				
0·50	21·4	17·2	80·0	16·8	78·4
0·75	22·3	16·9	75·7	16·7	75·3
1·00	21·1	15·4	73·3	15·4	73·2
	BEST BOILER RIVET STEEL.				
0·50	21·8	17·2	79·1	17·5	80·6
0·75	21·0	16·2	77·0	16·2	77·2
1·00	22·0	16·1	73·2	16·2	73·4
	STRUCTURAL RIVET STEEL				
0·50	24·7	19·4	78·3	18·4	76·0
0·75	25·0	18·6	74·6	18·7	74·9
1·00	24·0	17·0	70·9	17·2	72·0
	WROUGHT IRON.				
0·50	22·2	18·0	81·5	17·0	79·5
0·75	22·4	17·2	77·0	17·5	79·8
1·00	21·6	15·7	72·8	16·2	75·2

effect produced, because this would have the opposite tendency, and give a lower shearing strength for the smaller bars. The author of the paper in which the experiments are described suggests that the lower shearing strength of the larger bars is probably due to the fact that the bearing stress must be greater in this case, greater indentation is produced, and probably this leads to the shearing taking place at lower loads.

101. Choice of Shearing Tackle.—Some difficulty may be experienced in choosing a suitable form of apparatus for the purpose of carrying out shearing tests. In any shear-

ing tackle, the two most important conditions for accurate testing are, first, that the load be applied in a direction truly at right angles to the centre line of the test bar, and, secondly, that there should be no possibility of a bending stress being introduced. The latter condition can only be attained by the bar being rigidly held in its place and being allowed no play or freedom. In order that this may be so the bar must either be very accurately turned and fitted into the holes, or it must be firmly bolted in its place, as in the Johnson gear, which has been described. The true direction of the load is more easily preserved in a gear in which the load is applied in a tension machine than when applied in a compression machine. Probably a form of tackle in which the holding arrangements of Professor Johnson were combined with an attachment for holding and applying the load in a tension machine, instead of as at present, between the compression plates, would be as reliable as any.

CROSS-BREAKING TESTS.

102. Systematic tests of materials under cross-breaking stresses often require more preparation and more elaborate appliances than tests in tension; but for some purposes and for some materials they provide valuable information, and serve their purpose better. For instance, bending tests of cast iron are more easily carried out, and, as a rule, are more reliable than those in tension. Timber, again, is most frequently subjected to bending stresses when in actual use, and bending tests provide the most reliable information as to its qualities for the purposes for which it is to be utilised. Wrought-iron and steel, though not usually tested under bending stresses in the form of small test pieces, are frequently tested as rolled joists and girders, and in some cases in the form of actual built-up beams; this also applies to rails of various sections.

103. Testing Appliances used in Cross-breaking.—As we have already seen, most testing machines intended for general work are provided with special parts for the carrying out of bending tests. In addition to these, there are many small machines designed and used almost exclusively for work of this kind. The plan adopted is very much the same in all cases. To one of the shackles of the machine—

say, the load-measuring shackle—a heavy, stiff beam is attached, at or near the ends of which are two supports, upon which rests the beam to be tested, and which at the same time determine the span; to the other shackle is attached a stirrup carrying a knife-edge, which is made to press upon the centre of the beam to be tested, and thus forms the point at which the load is applied. In some cases the points of support are simple steel knife-edges, in others the ends of the beam are allowed to rest upon prisms of steel, of semi-circular section, with the flat faces

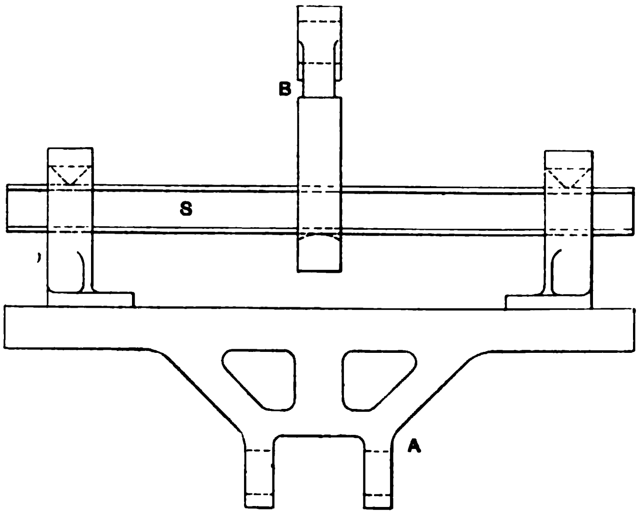


FIG. 81.

against the specimen. The semi-cylindrical surfaces rest in bearings of corresponding form, and as the beam bends under the load, these plates move slightly in their bearings, and in this way accommodate themselves to the varying form of the beam. The span in this case is the distance between the centres of the cylindrical portion of the plates. This arrangement is shown well in the case of one of the smaller Buckton-Wicksteed machines in Fig. 26. Here the supports are shown, but the semi-cylindrical plates are not in position. Reference should also be made to Figs. 27, 31, 32, 33, 35, and 36. In the case of the Sydney machine, on Fig. 27, the load is measured through a stirrup hung from the tension shackle, and the supports are formed on the ends of rams working in

cylinders which are fixed in the two separate standards shown. By this means, beams of very much greater span than could be taken by the usual appliances can be tested. In the ordinary machines of 100 tons capacity, provision is usually made for testing beams up to spans of 5 ft. or 6 ft. In the Sydney machine the maximum span is 15 ft.

On Fig. 81 is shown the form of beam testing shackle as applied to a 100-ton vertical machine designed primarily for tension, and having no provision for compression or cross-breaking. Here the lower frame or beam A is attached, by means of a pin, to the lower tension shackle, and the stirrup, carrying the central knife-edge B, is hung

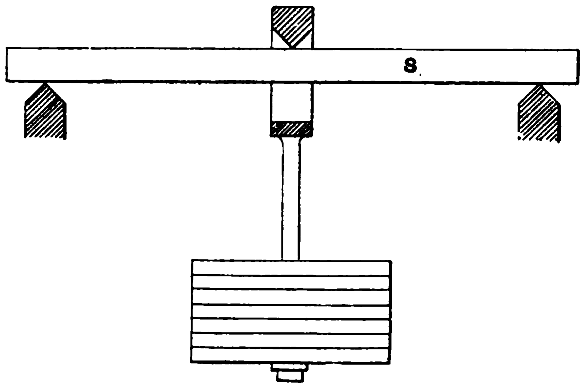


FIG. 82.

from the upper tension shackle. The supports for the ends of the specimen beams are knife edges pointing downwards, as shown. This is the form of shackle made for Professor Unwin, by Messrs. Buckton.

In all bending shackles provision is made whereby the span can be varied at will. The load is generally a concentrated one applied in the middle of the beam, which is itself supported at the two ends, but by a slight modification the load can be applied in a distributed form, or on two or more points. This, however, is rarely done.

At the present day, testing machines are so numerous that they can nearly always be obtained for beam testing purposes; but where a machine is not available, the beam may rest on fixed supports, and the load may be applied by hanging on a number of dead weights. This plan is illustrated on Fig. 82.

The supporting and loading of a beam under test is not as a rule difficult, but the measuring of the strains requires some special care. In a tension test, measurements can be made along the length of the bar, but in a bending test the strains are in a direction at right angles to this, and the supporting of the measuring apparatus is not so simple as in the former case.

104. **Deflectometers.**—These are, as their name implies, instruments for measuring the strains on a specimen under a transverse test. As in tension testing, the first and most important condition to obtain is that the instrument used shall be entirely supported by being attached to the specimen, and no measurements should be taken from parts of the testing machine itself. The reason for this is that the machine parts undergo strain themselves, and there may be small strains of the beam due to the compression of the

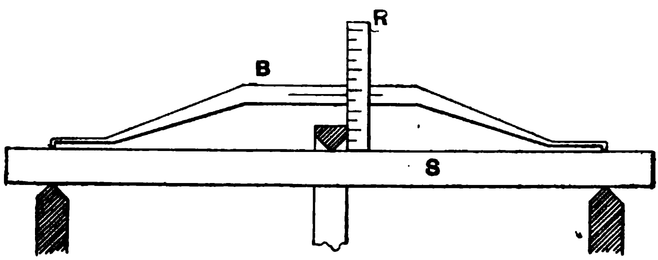


FIG. 83.

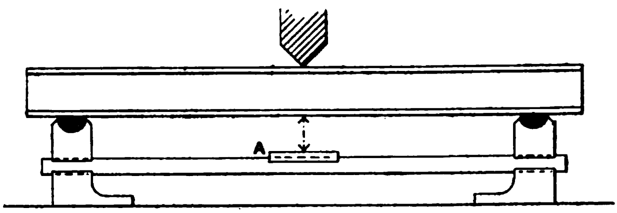
material on the points where it bears on the supports. Strains due to either or both of these causes will be recorded as part of the legitimate bending strain, and are therefore to be avoided. In cases where the span of the beam is great relatively to the depth, and consequently the bending strains are relatively great, and also when the supports are of the rolling or rotating kind, and there is likely to be very little indentation of the specimen, it is sometimes permissible to transgress the rule and to measure the deflections from a frame attached to the supports near the beam itself, and the likelihood of error will be small. But it is advisable, when it can possibly be arranged, to have the measuring gear wholly supported by the specimen.

In the rougher kind of tests, such as those carried out on bars of cast iron, and where it is not required to determine the modulus of elasticity, the measurements of strain may be made with a steel rule divided into hundredths of an inch. The arrangement of this is shown on Fig. 83.

Here the beam to be tested, marked S, is shown supported at the two ends, and having the load applied in the centre. B represents a light but sufficiently stiff frame, held to the bottom of the beam by means of spring clips. As the loads on the specimen increase, it will be bent, but the measuring frame will retain its original shape. The measurements of the deflections may be determined by applying the steel rule, R, and taking the deflections direct. The measuring frame may be made of either metal or wood; if of the latter, a small plate of brass should be affixed to it so as to provide a sharp edge, or a line, to measure from.

Strictly speaking, the measuring bar, the points of support of, and the point on the beam from which the measurements are taken should be in the neutral axis of the beam, as it is in reality the deflection of this that is

FIG. 84.



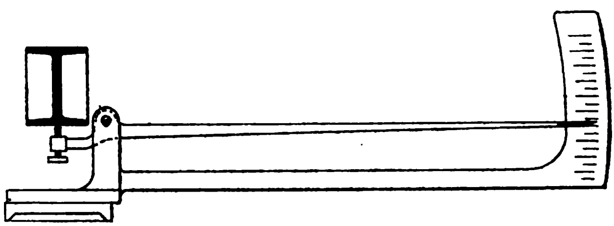


FIG. 85.

wanted; but it is more convenient to attach it loosely to the surface of the beam, especially as, if the bar is attached this way, there is less likelihood of its being broken when fracture takes place and the two parts of the beam fall to the ground, and the error involved is relatively small. A more permanent measuring apparatus than that described may be arranged by having the steel rule attached to the measuring bar during the test.

Provision is made on some of the Buckton-Wicksteed machines for measuring the deflections of beams by means of a plate, A (Fig. 84), supported below the beam

which is being tested upon two steel bars, fitting at the two ends into the brackets which carry the revolving supports. During a test the deflections may be either measured directly from this plate to the under-surface of the beam by means of a pair of ordinary calipers, an inside micrometer caliper, or a separate multiplying deflectometer, like the one shown in Fig. 85.* This instrument is simply a lever of large multiplying ratio clamped to the plate, and having the short end of its lever resting against a point on the underside of the beam. The end of the long arm forms a pointer, which is arranged so as to move over a fixed vertical scale, and the deflections of the beam are the readings on the scale multiplied by the velocity ratio of the lever. This arrangement is found to work very satisfactorily, in spite of the fact that it is in principle faulty in one or two respects—as, for instance, the support of the measuring lever is not carried by the beam itself. The error introduced from this cause is very small, because the heavy design of the supporting brackets and the large bearing surface upon which the beam rests render it difficult for any appreciable yield to take place.

For given loads, the deflections are relatively great as compared with the extensions of a tension piece for the same loads, and therefore the measuring gear need not be of quite so delicate a character, especially for large beams. In the multiplying gear that has just been described, a lever ratio of 10 to 1 is found to work well for beams of 5 ft. span or upwards, but a larger ratio may with advantage be employed.

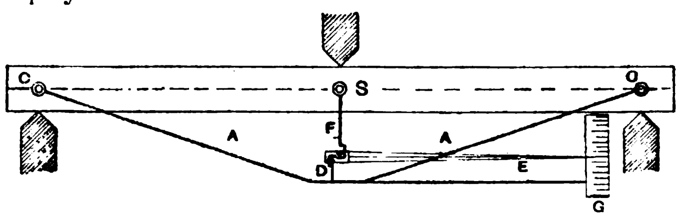


FIG. 86.†

For small beams a gear similar to that shown diagrammatically on Fig. 86 may be used. In this arrangement, A is a light frame carried by the specimen S itself, which it clips through two pairs of screws C C. At the centre of

* See Secundo on Beams, Proc. Inst. C.E., Vol. XCVIII., p. 32; also Carpenter's "Experimental Engineering," p. 115.

† This is similar in principle to the instrument used by Professor Goodman at the Yorkshire College.

this frame is a plate D, upon which rests the end knife edge of a multiplying lever E; the second knife edge of this lever is pressed upon by a stirrup F, attached to the centre of the beam, also by a pair of screws. These two sets of attachments must all be made on the neutral plane of the beam, and those which support the frame should be vertically above the supports of the beam. The end of the long arm of the lever forms a pointer which moves across the graduated scale G. Readings to one-thousandth of an inch can easily be obtained. A gear of this kind is exceedingly useful for deflection measurements of all small beams, and for the elastic deflections of cast-iron beams. The frame A should be pivoted to the gripping screws, C, at one end, and at the other simply rest upon the screws, so that the shortening of the distance C C during deflection will not distort the frame and so cause errors.

Each material used in the construction of beams has its own characteristic behaviour under stress. Cast iron invariably breaks, and the strains before failure are comparatively small. Wrought iron and steel cannot as a rule be broken, but take a large amount of permanent set. Fracture does occur occasionally in steel beams when the metal is too hard. Timber fails by first crushing on the compression side, and then actual rupture takes place by the tearing apart of the fibres on the tension side. For the purpose of measuring the deflections on a large timber beam, a fine wire may be stretched tightly across between the two ends of the neutral axis, and measurements taken from this to the line denoting the neutral axis, which has been previously marked upon the surface of the beam.

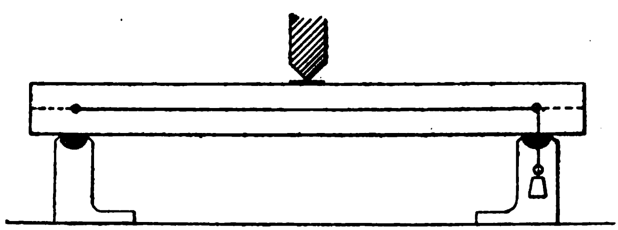


FIG. 87.

This is shown on Fig. 87. The wire itself may be attached at one end to a nail driven into the beam and kept tight by being made to pass, at its other end, over a second nail or a small pulley, and carrying a weight. This method

was used by Barlow for measuring the deflections of metal beams, a fine steel wire being employed.

105. Testing of Cast-iron Beams.—The commercial test for the quality of cast iron is most frequently carried out upon a beam of rectangular section. This is more easily performed than a tension test, and yields more uniform and reliable results. The size of beam adopted for this purpose is most generally either a 1 in. square section, tested on a 1 ft. span; or in some cases the span may be 3 ft.; or the section is rectangular, 2 in. deep, 1 in. broad, upon a 3 ft. span. The information required from the test is the breaking load applied at the centre, the deflection at the centre when fracture takes place, and the nature of the surface of the fracture itself.

The test may be carried out either in a testing machine, or by the application of dead loads. Of these the former is by far the more convenient, but deadweights may be used when a machine is not available. Several of the testing machine makers supply machines of small capacity, specially adapted for the tests of cast-iron beams. If the beam is of a 2 in. by 1 in. section on a 3 ft. span, the load is to be gradually applied, and the deflection measured, say, at every 500 lb. increment of load until fracture takes place. In connection with tests of this kind it is important, as affecting the result, to place the beam in the proper

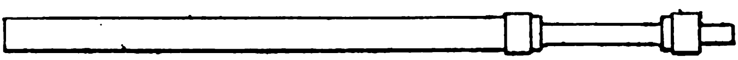


FIG. 88.

position in the machine. A beam is most often cast edgewise, the vertical section being slightly taper. It would at first sight appear that in order to obtain the higher result from the test, that edge which has the greater width should be placed so as to form the tension surface. This would be so if the metal were uniform, but it will most often be found that the better and stronger metal is at the lower or narrower edge, and the worst metal is to be found on the upper edge, and therefore this must be put in compression. Mr. Kirkaldy recommends that, in a commercial test of cast iron, three test pieces should be cast in one, so that the metal may be of a uniform character throughout. A combined bar of this kind is shown on Fig. 88. The casting

should be made with the pattern placed in the mould with the greatest depth vertical, and the bar in a horizontal position. After the casting has been taken out of the sand the separate pieces can be cut off, thus forming a beam for a bending test, a tension specimen, and a compression specimen.

When a bar is tested under a cross-breaking stress the central load is to be gradually applied until fracture takes place by the tension side failing, and the beam breaking into two parts. At the same time as the load is being increased the deflections must be measured at frequent intervals, the readings being taken more frequently as the point of fracture is approached. These deflections may be most suitably measured directly from a light frame attached to the beam itself, as has been described.

From the fact that it is unusual to get a number of castings of *exactly* the same dimensions, and still less frequently of the nominal dimensions, it is the common practice to ascertain the dimensions of the beam, and then to calculate the load which *it would have taken* to fracture a bar of the nominal dimensions. For instance, if the nominal dimensions of the beam are 2 in. deep and 1 in. wide, and the actual dimensions are found to be 2·04 in. deep and 0·98 in. wide, the result must be reduced to *what it would have been* if the dimensions had been 2 in. by 1 in. This can be done by taking it that the strength varies directly as the width, and directly as the square of the depth. The reason for doing this is obviously in order to preserve uniformity and to help comparison. It is analogous to reducing the breaking loads on tension bars to so many pounds or tons *per square inch*. An example of a test of this kind is given so as to show the method of working out the results.

TEST OF A CAST-IRON BEAM.

Original Dimensions.—Depth, 2·03 in.; width 1·04 in.

LOADS. Lb.	DEFLECTIONS. In.
500	0·046
1000	0·095
1500	0·150
2000	0·200
2500	0·260
3000	0·340
3125	0·360 breaking load

To find the "equivalent breaking load" on the standard 2 in. × 1 in. section. We know that

$$\frac{(\text{width}) \times (\text{depth})^2}{\text{span}}$$

is proportional to the breaking load in the centre. Or, if W_1 is the actual breaking load and W is the similar load for a 2 in. × 1 in. section and 36 in. span, then,

$$\frac{W}{W_1} = \frac{\frac{1 \times 2^2}{36}}{\frac{b\,d^2}{l}}$$

where b, d, and l are the width, depth, and span respectively of the broken beam.

Or, $$W = W_1 \frac{4\,l}{b\,d^2\,36}.$$

As the span l can generally be varied at will, and is usually set to 3 ft., l may be taken = 36, and the equation reduces to

$$W = \frac{W_1\,4}{b\,d^2}$$

In the above example,

$$W_1 = 3125 \text{ lb.}$$
$$b = 1{\cdot}04 \text{ in.}$$
$$d = 2{\cdot}03 \text{ in.}$$

So that, using these values,

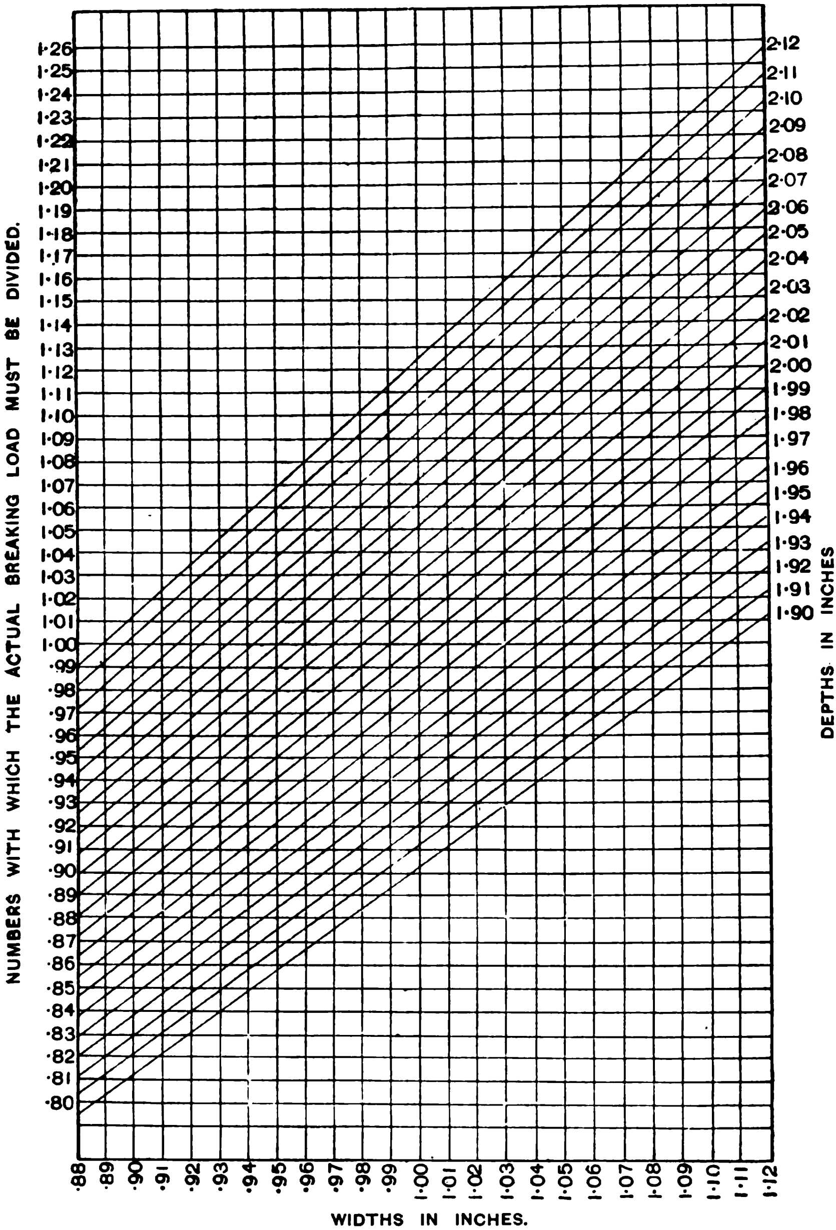
$$W = \frac{3125 \times 4}{1{\cdot}04 \times (2{\cdot}03)^2}$$
$$= 2910 \text{ lb.}$$
$$= 26 \text{ cwt.}$$

The results thus obtained may be put on a report form somewhat as follows:—

REPORT OF TEST OF CAST-IRON BEAM.

Number of Test.	Span. Inches.	Dimensions.		Central Breaking Load. Pounds.	Equivalent Breaking Load on 2″ × 1″ Section. Pounds.	Maximum Deflection. Inches.	Equivalent Breaking Load. Cwt.
		Width. Inches.	Depth. Inches.				
542	36	1·04	2·03	3,125	2,910	0·36	26·0

Fig. 89.—Diagram of Ratios of Actual Breaking Loads of Cast-iron Beams to Equivalent Breaking Loads on a 2 in. × 1 in. Section.



The measurements of the dimensions of the beam should be made at the actual point of fracture after the specimen has been broken. The nature of the fracture should be referred to in the report, and a statement made as to whether it is "fine-grained" or "coarse-grained," "sound" or otherwise.

The deflection of a cast-iron beam of these dimensions will be found to be roughly one-tenth of an inch for each 1,000 lb. of load.

The equivalent load on a 2 in. by 1 in. section may be more readily obtained by making use of a table of multipliers, calculated for sections of various dimensions; or by means of the accompanying diagram (Fig. 89.) The use of this diagram can be best explained by showing how it is applied to the above case.

Here the depth and width were respectively 2·03 in. and 1·04 in., and the actual breaking load 3,125 lb.

To use the diagram, first look along the base line and find the vertical ordinate corresponding to 1·04 in. Then follow this ordinate upwards until it meets the one of the sloping lines corresponding to the depth. Then the height of this point, measured along the ordinate to the vertical scale of the diagram, will give a number with which to *divide* the load, in order to obtain the equivalent load.

In the present case, this is 1·072. So that the equivalent breaking load on a 2 in. by 1 in. section is

$$\frac{3,125}{1·072} = 2,910 \text{ lb.},$$

which is the same result as was obtained by the previous method.

The test which has just been described is of the kind which is carried out for purely commercial purposes. A test of a similar cast-iron beam under more complete conditions, so as to provide detailed information as to the properties of the metal, will now be described. The span is supposed to be the same as before, and the section is again approximately 2 in. by 1 in. In the present instance, however, the increments of load are relatively small, and the deflections are measured at much more frequent intervals in order to determine the modulus of elasticity with accuracy. In a case of this sort the deflections must be measured by means of a deflectometer, of the form indicated on Fig. 86, page 176. The actual process of making this test is as follows: The beam,

after being carefully measured, is placed in the machine with one of its narrow faces resting on the supports. The deflectometer is now fixed in place, care being taken that the points of attachment of the instrument coincide with the neutral surface of the beam, and that the two outer points are exactly over the points of support. When the pointer of the deflectometer has been set to the zero of its scale the test may proceed. In the case of a cast-iron beam of this size, it will be found convenient and sufficient to take deflection readings at increments of 50 lb. It will be seen, on referring to the table of figures, that readings are recorded at every 50 lb. up to 1,500 lb., and after that at intervals of 200 lb. The meaning of this is that the readings at the small intervals were taken with the deflectometer. After this the instrument was removed, and direct measurements made with a steel rule from a frame like that shown on Fig. 83, page 174, or from the frame of the deflectometer itself. By thus removing the instrument before the point of fracture is nearly approached it is saved from any damage that it might suffer if the beam fractured when it was in place; and, moreover, the readings obtained up to this point are quite sufficient for the purpose required. Great care should be taken that the second series of measurements are continuous with the first.

TEST OF A CAST-IRON BEAM.

Depth.................. 2·00 in.
Width .... 1·03 in.
Span .... 36 in.

Loads. Pounds.	Deflections. Inches.	Remarks.
50	0·003	
100	0·007	
150	0·012	
200	0·017	
250	0·022	
300	0·026	
350	0·031	
400	0·035	
450	0·040	
500	0·044	
550	0·049	
600	0·053	
650	0·060	
700	0·065	
750	0·089	
800	0·073	
850	0·078	
900	0·082	
950	0·087	
1,000	0·092	
1,050	0·096	
1,100	0·100	
1,150	0·105	
1.200	0·110	
1.250	0·115	
1.300	0·120	
1,350	0·125	
1,400	0·130	Deflectometer removed.
1,600	0·150	
1,800	0·170	
2 000	0·200	
2,200	0·220	
2,400	0·250	
2 600	0·270	
2 800	0·300	
3,000	—	Broke at this point.

These are the actual figures obtained during the test. It may be pointed out that it is always well to repeat the deflectometer readings two or three times to make sure of getting a sensibly uniform set. It will now be necessary to reduce the above figures, so as to get the average deflection. Taking the maximum possible intervals

of 700 lb., it will be found that the following differences will be obtained :—

0·130	0·125	0·120	0·115	0·110
0·065	0·060	0·053	0·049	0·044
0·065	0·065	0·067	0·066	0·066
0·105	0·100	0·096	0·092	0·087
0·040	0·035	0·031	0·026	0·022
0·065	0·065	0·065	0·066	0·065
0·082	0·078	0·073	0·069	
0·017	0·012	0·007	0·003	
0·065	0·066	0·066	0·066	

Taking the average of these—

$$\begin{array}{r} 0·065 \\ 65 \\ 67 \\ 66 \\ 66 \\ 65 \\ 65 \\ 65 \\ 66 \\ 65 \\ 65 \\ 66 \\ 66 \\ 0·066 \\ \hline 14)\,0·918 \end{array}$$

$$0·0656 = \left\{ \begin{array}{l} \text{inches deflection per each 700 lb} \\ \text{load applied at the centre.} \end{array} \right.$$

It has already been pointed out that the Modulus of Elasticity of a beam under the given conditions is expressed by the formula :—

$$E = \frac{W \, . \, l^3}{48 \, . \, \delta \, . \, I}$$

Here,

W = the central load, 700 lb.

l = the span, 36 in.

= the deflection corresponding to W, 0·0656 in.

I = the moment of inertia.

$$= \frac{(\text{breadth}) \times (\text{depth})^3}{12}$$

$$= \frac{1·03 \times (2)^3}{12}$$

$$= 0·69.$$

Putting in all these values—

$$E = \frac{700 \times (36)^3}{48 \times 0{\cdot}0656 \times 0{\cdot}69}$$
$$= 15{,}160{,}000 \text{ lb. per sq. in.}$$
$$= 6{,}750 \text{ tons per sq. in.}$$

By again making use of the diagram on Fig. 89, p. 181, the equivalent load on a 2 in. × 1 in. section can be found.

$$\text{Equivalent breaking load} = \frac{W}{1{\cdot}03}$$
$$= \frac{3{,}000}{1{\cdot}03}$$
$$= 2{,}910 \text{ lb.}$$

It has been shown that the maximum stress in bending,

$$f_b = \frac{M}{Z}$$

M being the bending moment at the section in question, and Z being the "modulus of the section," which in this case is

$$Z = \frac{b\,d^2}{6}$$

For a beam loaded centrally and supported at the ends, the maximum bending moment

$$M = \frac{W \, . \, l}{4},$$

the symbols having the same meaning as before, so that

$$f_b = \frac{W\,l}{4} \cdot \frac{6}{b \, . \, d^2} \, .$$

Now, in the present instance,

$$W = 3{,}000 \text{ lb.}$$
$$l = 36 \text{ in.}$$
$$b = 1{\cdot}03 \text{ in.}$$
$$d = 2{\cdot}00 \text{ in.}$$

Putting these values in the above expression,

$$f_b = \frac{3{,}000 \, . \, 36 \, . \, 6}{4 \quad 1{\cdot}03 \, . \, 4}$$
$$= 694{,}000 \text{ lb. per sq. in.}$$
$$\text{or} \quad = 17{\cdot}6 \text{ tons per sq. in.}$$

In order to compare the modulus, as obtained from the cross-breaking tests, with that obtained from direct tension, one of the broken halves of the beam may be put in the machine as a tension specimen, and treated in the usual way. Without giving all the figures in detail, it will be sufficient to quote the results obtained for such a test applied to the case in question.

Here,

$$\text{area of the section} = 2{\cdot}00 \times 1{\cdot}03 = 2{\cdot}06 \text{ sq. in.}$$

$$\left.\begin{array}{r}\text{Mean extension}\\ \text{per ton of load}\end{array}\right\} = 0{\cdot}0073 \text{ in.}$$

The elastic modulus

$$E = \frac{f \cdot L}{l}$$

$$= \frac{1}{2{\cdot}06} \times \frac{2240}{1} \times \frac{10}{0{\cdot}0073}$$

$$= 14{,}900{,}000 \text{ lb. per sq. in.}$$

$$= 6{,}600 \text{ tons per sq. in.}$$

This result agrees fairly well with the modulus as obtained from the bending experiment.

Care should be taken to discriminate clearly between the maximum stress in a bar of cast iron, as given by a test in direct tension, and the maximum stress as calculated from the breaking load in a cross-breaking test by the ordinary beam formula. For a beam of a perfectly elastic substance the beam formula does truly express the relation existing between the load, the dimensions, and the stress in those fibres furthest away from the neutral surface. But this is true only so long as the beam does retain its elasticity, and as soon as the limit has been passed the formula no longer holds. In the case of cast-iron beams, the elastic state ceases to exist before actual rupture occurs, and the maximum stress, as calculated from the breaking load by the beam formula, does not correspond to the maximum stress, as deduced from a direct-tension test. In fact, these two bear to one another no constant ratio, except that the bending stress is always greater than the tension stress, and less than the compressive stress for the same metal. The precise relation between the two depends very largely upon the form of the cross-section. It is therefore wrong

to attempt to foretell the strength of a cast-iron beam simply from a knowledge of the tensile strength of the metal.

On Fig. 90 is shown a complete load-strain diagram plotted from the figures obtained in the above bending test. The actual plotted points are indicated as before by

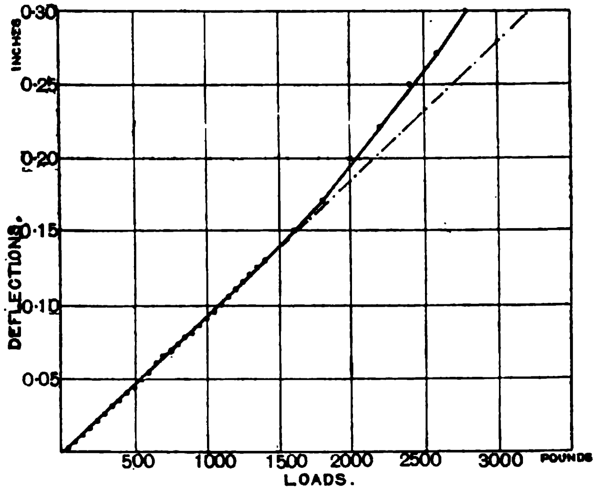


FIG. 90.—Deflection Diagram for a Cast-iron Beam.

the centres of small circles. It will be noticed that, up to a load of about 1,500 lb., the points lie on a sensibly straight line, but, beyond this point the diagram curves upwards, as shown by its deviation from the dotted line. This upward curvature may be taken as indicating a departure from the truly elastic conditions. As a matter of fact, very careful experiments have shown that even at the lowest loads cast iron is not elastic in the strict meaning of the word.

106. Testing of Wrought Iron and Steel Beams.—Beams of these metals may be tested in all sizes, so long as the necessary loads do not go beyond the capacity of the machine which is to be used for the purpose. Generally speaking, plain rectangular bars are not often tested as beams, the most usual forms being rolled joists, built-up beams, girders, and rails of various forms. The example that will be taken for the purpose of illustrating this part

of the subject is that of a steel rolled joist, 6 in. by 6 in. by ½ in. The span upon which this beam is tested is 5 ft.; that is to say, there are 5 clear feet between the points of the V supports, if such are used, or 5 ft. between the centres of the rotating supports, if these are employed. Frequently it is found that the specimen is slightly twisted or distorted, and when this is found to be so, it is necessary to place some thin packing between the beam and its supports, in the centre of its width, in order that the reactions of the supports may come directly in the centre of the beam, and not, as is sometimes the case, upon one or other of the flanges. In cases where the section is not symmetrical about a vertical centre line, any extra packing that is required must be placed directly beneath the web.

The load is usually applied at a point exactly midway between the two outer supports, and the point of application of this load is most frequently in the form of a V. This V should have its edge dull or rounded, as it will be

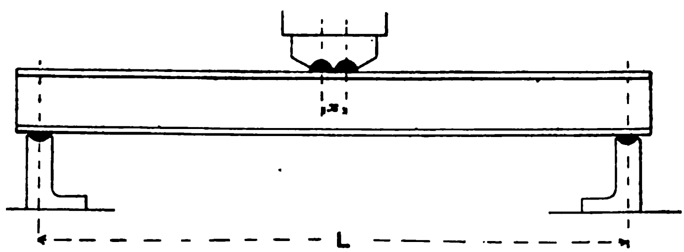


Fig. 91.—Buckton's Presser Foot for Cross Bending Tests. Effective Span = L - x.

found that a sharp edge penetrates the metal and damages the flanges of the specimen. To obviate this, unless the V is made dull, a flat strip of steel about 1½ in. wide may be inserted between the V and the specimen. An ingenious way of overcoming this difficulty has been devised by Messrs. Buckton and applied to the machine used by Mr. Charnock at the Bradford Technical School. The principle of this is shown on Fig. 91. Here, instead of the load being applied at one point, a pair of rotating plates are employed similar to those used in some cases for the end supports. By this means the load is more evenly distributed, and the plates yield by rotation as the beam

bends. In reckoning the length of span the distance between the centres of these two plates must be subtracted from the total length.

Assuming that the specimen has been arranged in such a way that the load will come upon it exactly in its centre, and that there will be no tendency for the beam to be twisted or distorted by the load, the next thing to be provided for is the measurement of the deflections produced by the loads imposed. In the absence of a special instrument similar to the one used in the test of a cast-iron beam just described, the best arrangement that can be adopted is that shown on Figs. 84 and 85, page 175. It is easy to construct and not costly, and at the same time may be relied upon to give readings sufficiently accurate. In fixing this apparatus, care should be taken that, in the first place, the end of the short arm of the lever which comes into contact with the under side of the beam is applied beneath the exact centre of the web, and not under one of the flanges, as the curvature of the flanges may not be quite the same as that of the beam as a whole; and, secondly, the bracket which carries the fulcrum of the multiplying lever should be rigidly and immovably fixed to the plate beneath the middle of the beam, and not allowed to come into contact with any object external to the testing machine. It will be found convenient to have the ratio of the multiplying lever so arranged as to be a whole number, such as 10 or 25. When this is so the scale of instrument can be formed of a steel rule divided into tenths and hundredths of an inch; or a piece of squared paper may be used, but care must be taken that the divisions on the paper are accurately what they are represented to be.

When the specimen has been fixed in the machine and the deflectometer attached, its pointer may be set to zero by means of the adjusting screw, and the test proceeded with, the increment of load employed being selected to suit the case in question. In the present example, readings were taken at every ton of load. The elastic readings may be kept well within the limit, or they may be carried just beyond this point, until a definite permanent set has taken place; or, again, the load may be increased until the maximum load which the beam will carry has been reached. In the present instance the second of these plans was adopted. The following is a record of the complete test.

BENDING TEST OF A STEEL JOIST.

Depth	6 in.
Breadth	6 in.
Thickness	$\frac{1}{2}$ in.
Span	5 ft.

Moment of inertia of the section, 55·9.

Loads in Centre. Tons.	Deflections. Inches.	Remarks.
1	0·006	
2	0·013	
3	0·020	
4	0·027	
5	0·034	
6	0·040	
7	0·046	
8	0·052	
9	0·058	
10	0·065	
11	0·071	
12	0·077	
13	0·084	
14	0·090	
15	0·096	
16	0·102	
17	0·110	
18	0·117	
19	0·126	
20	0·139	
21	0·151	
22	0·167	
23	0·188	
24	0·216	
25	0·256	
26	0·309	
27	0·371	
28	0·449	
29	0·547	
30	0·662	

From these observed results, the elastic modulus for the material can be calculated.

It will be remembered that the Modulus of Elasticity,

$$E = \frac{W.l^3}{48.\delta.I}.$$

First, to find the deflection corresponding to a central load W. From the above figures it will be seen that the increments of deflection are sensibly uniform up to a

load of about 16 or 17 tons. So that, taking the readings up to that point, and taking the differences as before, the following results are obtained:

0·102	0·096	0·090	0·084	0·077
0·052	0·046	0·040	0·034	0·027
0·050	0·050	0·050	0·050	0·050

0·071	0·065	0·058
0·020	0·013	0·006
0·051	0·052	0·052

Taking the mean of these—

$$\begin{array}{r} 0{\cdot}050 \\ 0{\cdot}050 \\ 0{\cdot}050 \\ 0{\cdot}050 \\ 0{\cdot}050 \\ 0{\cdot}051 \\ 0{\cdot}052 \\ 0{\cdot}052 \\ \hline 8)\,0{\cdot}405 \\ \hline 0{\cdot}0506 \end{array} \left\{ \begin{array}{l} \text{inches = average deflection per} \\ \text{8 tons increment of load.} \end{array} \right.$$

For a section such as the one in question, which is not perfectly uniform, the best way to obtain the Moment of Inertia is by the graphic method, but here it will be sufficient to make use of the following approximate formula:—

$$I = \frac{B\,H^3 - b\,h^3}{12}$$

$$\begin{aligned} \text{Here } B &= 6 \text{ in.} \\ H &= 6 \text{ ,,} \\ b &= 5 \text{ ,,} \\ h &= 5 \text{ ,,} \end{aligned}$$

the thickness being $\frac{1}{2}$ in.

So that,

$$I = \frac{(6)^4 - (5)^4}{12}$$

$$= \frac{1296 - 625}{12} = 55{\cdot}9.$$

The values of the symbols in the formula are therefore—

$$\begin{aligned} W &= 8 \times 2{,}240 = 17{,}920 \text{ lb.} \\ l &= 60 \text{ in.} \\ \delta &= 0{\cdot}0506 \text{ in.} \\ \text{and} \quad I &= 55{\cdot}9. \end{aligned}$$

Therefore—

$$E = \frac{17920 \times 216000}{48 \times 0{\cdot}0506 \times 55{\cdot}9}$$
$$= 28{,}600{,}000 \text{ lb. per square inch.}$$
$$\text{or,} \quad = 12{,}750 \text{ tons per square inch.}$$

The load at which the elastic limit occurs is not so easy to determine in the case of a bending test as in simple tension. In a tension test the stress is uniform over the whole section, and, as soon as the stress gets beyond the limit, the increased increment of strain is easily recognised; but in a beam the stress is variable over the section, being greatest in those fibres farthest from the neutral plane. So that when the limit is reached it is only in those fibres which are subjected to the maximum stress, while the greater part of the section is still under stresses which are accompanied by elastic strains. The limit effect, therefore, only takes place very gradually, beginning at the outer

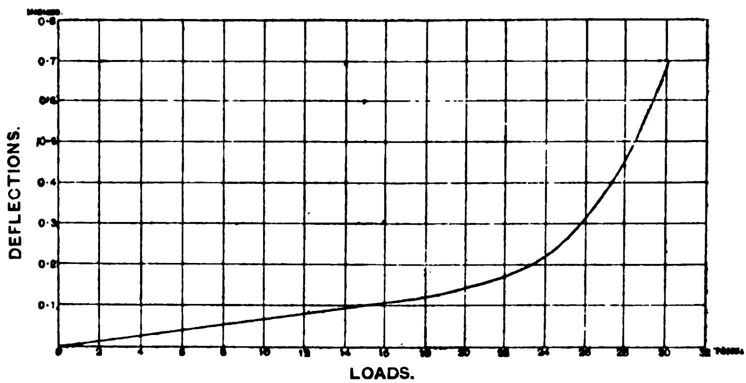


FIG. 92.

fibres and slowly penetrating inwards towards the neutral plane, and there may be a considerable interval in the loading between the point when the outer layers are stretched beyond the elastic limit and the time when the whole section is brought to this state. The gradual nature of the appearance of the limit will be appreciated by an inspection of the diagram on Fig. 92, which has been plotted from the figures given above.

By placing a straight-edge along the elastic portion of this curve it will be seen that it begins to curve away from the straight at a load of about 18 tons, and that point may

be taken as the elastic limit. The stress at which this occurs may be found in the usual way as follows:—

Here,

$$M = \frac{f \cdot I}{Y}$$

Where the symbols have the following meanings:

M = the bending moment at the centre, when the limit occurs.

$$= \frac{W \cdot l}{4}$$

f = the corresponding stress.
I = the moment of inertia,
= 55·9, as before.
Y = the distance from the extreme layers to the neutral surface,
= 3 in.

So that,

$$f = \frac{W \cdot l}{4} \cdot \frac{Y}{I}$$

$$= \frac{18 \times 60 \times 3}{4 \times 55 \cdot 9}$$

= 14·5 tons per square inch

The value of the stress f, obtained above, is, as nearly as can be determined, the stress on those fibres of the beam which are first strained beyond the elastic limit.

The loads may be carried beyond this point until one is reached which the beam is no longer able to support, when the test is at its natural end. When this maximum load is approached the deflection of the beam as a whole is often accompanied by a crippling of the flanges, and sometimes of the web.

It is only up to the elastic limit that the conditions represented by the ordinary beam formula obtain. The assumptions upon which the formula is based cease to be true after the elastic limit has been passed.

The transverse loads applied to a beam produce not only deflections due to the bending stresses, but deflections produced by the shearing stresses which exist on planes perpendicular to the neutral surface.* In the case of beams of large span and small depth this shearing strain is small, and may be neglected; but where the span is

* This point is discussed in Johnson's "Materials of Construction," p. 66.

small relatively to the depth it becomes of considerable importance, and must be taken into account. In order to avoid the complication due to this cause, it is best to make the span as large as possible. For rectangular beams the ratio of depth to span should not be less than one to ten, and may with advantage be one to twenty. For girder sections the span should be greater than this.

107. Testing of Timber Beams.—The most useful way of testing specimens of timber is in the form of beams supported at the ends, and loaded in the middle in a similar way to those which have been mentioned. Timber beam specimens may be of greatly varying sizes, from large full-sized beams, on spans of 15 ft., to small specimens 2 in. deep, 1 in. wide, and tested on a 36 in. span. For a perfectly homogeneous material $\frac{b \cdot d^2}{W \cdot l}$ may be taken to be a sensibly constant quantity, and small beams yield results just as reliable as those of larger ones. But timber is not a homogeneous material, and, owing to the fact that the grain is large relatively to the dimensions of a specimen, small pieces may yield results very different from large pieces of the same kind of wood. For this reason it is not advisable to employ pieces for testing purposes smaller than those last mentioned. If a commercial test is to be made on some one kind of wood a good many specimens should be tested, and an average taken, because no two pieces obtained from the same tree are quite alike.

The results aimed at in a commercial test of this kind are the central breaking load, and the deflection, either at the maximum load or at a certain specified load. It is not unusual to calculate the value of $\frac{b \cdot d^2}{W \cdot l}$ for the specimen in question, so as to provide a means of comparison with beams of other dimensions, but of the same material. This is also done in the case of some of the metals. For instance, in the case of the cast-iron beam whose test has been given above this value is as follows:—

$$\frac{b \cdot d^2}{W \cdot l} = \frac{1{\cdot}03 \times (2)^2}{3000 \times 36} = \frac{1}{26{,}200}.$$

This serves as a convenient way of comparing specimens of different dimensions.

It is not usual to measure the elastic deflections of timber beams with instruments of precision so as to ascertain the elastic modulus, but this may be done in some cases. A beam treated in this way will be found to possess a definite modulus, although there is considerable variation in its value, even in specimens of what is apparently the same material.

Some care is required in carrying out timber tests. Sharp knife edges should not be used, and where the testing machine is provided with supports of this kind, small steel plates must be inserted between the specimen and the knife edges, so as to distribute the pressure and prevent the edges penetrating the wood.

CHAPTER VI.

TESTING OPERATIONS—(*Continued.*)

TWISTING OR TORSION TESTS.

108. Rotating shafts are subjected to twisting or torsional loads, producing shearing stresses on planes at right angles to the axes of the shafts, acting in a rotary direction round these axes. The metals chiefly used for this purpose are iron and steel, and it is customary to subject small specimens of these metals to torsional stresses in testing machines, similar to those they may be expected to have to withstand when forming the actual parts of machinery. Measurements and observations made on specimens tested in this way yield more reliable information as to the behaviour of the metal in question than do tests in direct shear.

In addition to simple torsion, many shafts are subject to combined bending and torsion, as in the case of the crankshaft of an engine. There are few instances of cases where test pieces have been subjected to these combined stresses, and these have only been tests to destruction, where no attempt has been made to measure the elastic strains. The reason for this is that, though not insuperable, the difficulties of strain measurement are great in the case of combined bending and torsion.

The theory of simple torsion has already been considered, and a definite relation found to exist between the twisting moment on a circular shaft, the shearing stress at the outer surface, the dimensions of the shaft, and the modulus of transverse elasticity, G. There is also a relation found between the twisting moment, the dimensions, the angle of twist, and the modulus of transverse elasticity. In testing a shaft or torsion specimen it is possible to hold it in such a way that a moment of known magnitude is imposed, and at the same time the angle of twist or strain arising from this moment can be measured. In some of the rougher commercial tests it is not usual to measure the angular deflection, but simply the moment which is required to produce fracture.

Owing to the fact that shafts of circular section are by far the most commonly used this form is almost always employed for torsion specimens. The specimens should be turned, and provided with enlarged ends for holding purposes.

109. Torsional Testing Machines. — The conditions which must obtain in a test under a torsional stress, and the functions to be performed by the machine, are as follow: Imagine a truly circular bar of the metal to be tested. Then, in order that the test may be properly carried out:—

(*a*) One end of the bar must be rigidly held, and, at the same time, a twisting moment in the form of a couple applied at the other end, this couple acting in a plane at right angles to the axis of the bar.

(*b*) The usual manner of imposing the moment is by having a weight acting at the end of a single arm rigidly attached to one end of the bar, bending being prevented by having the enlarged end rotating in a long bearing.

(*c*) When the twisting moment is applied in the manner described, any strain which takes place causes the arm at which the load is applied to sink from its horizontal position, and, in order that this horizontal position may be at all times maintained, it is necessary to have some means of taking up the twisting strain.

(*d*) The shaft must be so held as to be free to vary its length, that is, one end must be free to move with respect to the other in the direction of its length.

(*e*) There must be no possibility of a distortion taking place in any way except in a rotary direction round the axis of the bar.

It is difficult to fully carry out all these conditions, and most existing machines have some defects. The general plan of most torsional testing machines is much the same, and is somewhat as follows:—

(*a*) The twisting moment is usually applied by means of a horizontal beam, provided with a jockey-weight, much in the same way as in an ordinary tension machine; in fact, some few machines are used for both torsion and tension tests. The bar to be tested is attached to the beam in such a way that its axis coincides with the axis of the knife-edge of the beam. The beam is provided with a hole into which the end of the test bar fits, not too tightly, and is held in place by keys or other grips.

(*b*) If the beam is initially floating horizontally, as the jockey-weight is moved outwards, the twisting moment on the bar is increased. The bar consequently twists or takes a torsional strain and the beam sinks from its horizontal position. The end of the bar remote from the beam must be held so as to be rotated at the will of the operator. This is generally accomplished by having the end of the bar fixed in the axis of a worm wheel, which can be rotated either by hand or power. The centre of the worm wheel is bored out so as to receive the end of the bar, which is prevented from rotating by keys.

In individual machines the details are varied somewhat but the general arrangement is the same in nearly all cases.

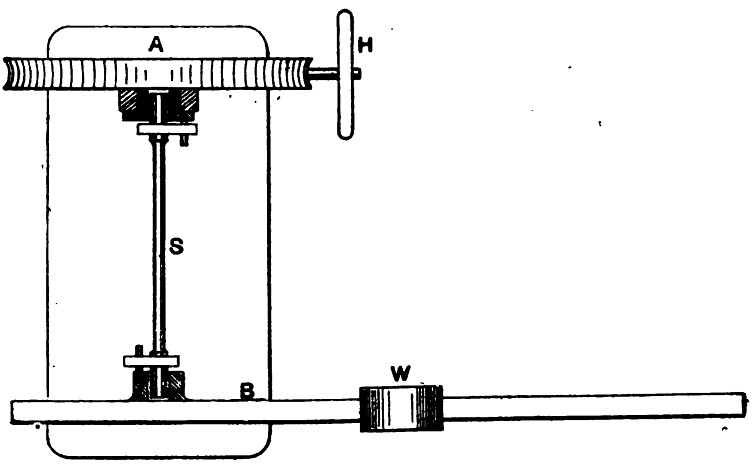


FIG. 93.—Kennedy's Original Torsion Machine.

110. Professor Kennedy's Torsional Testing Machine.—On Fig. 93 is represented in plan the arrangement adopted in Professor Kennedy's original torsional testing machine, and which forms the basis of most modern torsion machines. The view is diagrammatic. The specimen is marked S, and consists of a circular bar of the material to be tested, with turned ends. The end nearest the top of the page is made to fit easily into the boss of the worm-wheel marked A. The other end fits in a similar way into the boss of the steelyard B, the axis of the hole into which it fits coinciding with the line of the knife-edge about which the steelyard rotates. In order

that the ends of the bar may be free to move endwise these ends are gripped by two clutches or dogs, which themselves rest against pins in the worm-wheel and the beam respectively.

The twisting moment is put upon the specimen by the travelling weight W, the magnitude of this moment being

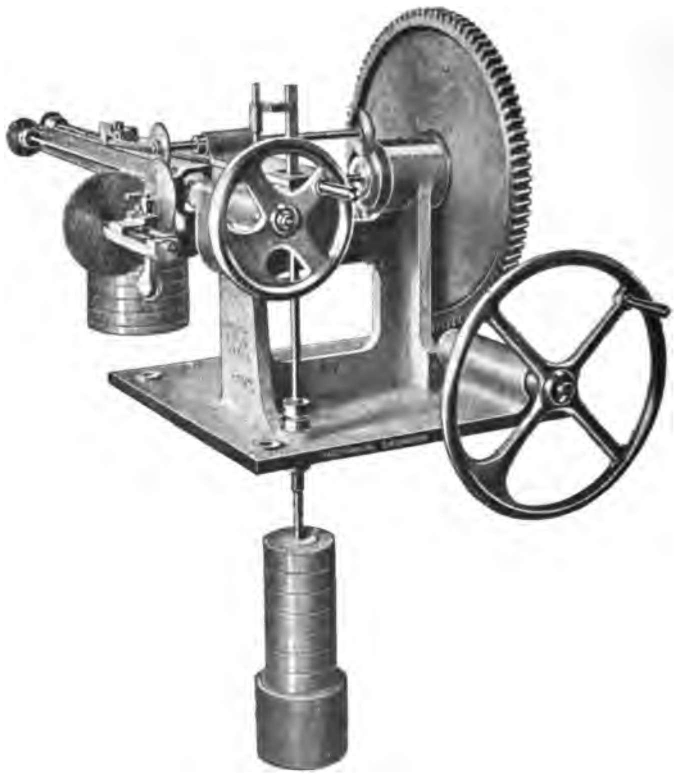


FIG. 94.—Buckton-Wicksteed Torsional Testing Machine.

the product of this weight, and the distance it has moved outwards from its position of equilibrium. The twist of the bar is taken up, and the beam kept floating horizontally, by means of the worm-wheel A, which is rotated by turning the hand wheel H, this being keyed on to the shaft carrying the worm which gears into the wheel.

Professor Kennedy* states that this machine is capable

*Min. Proc. Inst. C.E., Vol. lxxxviii., p. 39.

of exerting a maximum twisting moment of 4,000 inch-pounds. It is, therefore, suitable for testing specimens of mild steel up to about $\frac{5}{8}$ in. diameter.

111. Buckton-Wicksteed Torsional Testing Machine.—This machine, which is shown on Fig. 94, is similar in its general arrangement to the one which has just been described. One end of the specimen to be tested is held in the boss of the worm wheel, which is rotated by hand; the other end is attached to the beam of the machine. This beam rests upon a knife edge in the ordinary way, and carries a poise-weight, which will be seen hanging from the beam. The weight is moved along the beam by means of a screw, rotated by the small hand wheel shown in the photograph. In order that the movement of the beam may be unrestricted, the shaft which is used to communicate the motion to the jockey-weight screw, is connected with the hand-wheel shaft through a Hooke's coupling. The large weight, which is seen hanging from the short arm of the beam at the end of a long rod, is simply an adjustable weight used to balance the long end of the beam and the poise-weight in its initial position. The poise-weight consists of a number of loose discs hung on a vertical rod. By this arrangement the weight can be made variable within certain limits.

To the poise-weight carriage is attached a vernier, which slides along a scale fixed to the beam, and in this way indicates the number of inches and the fraction of an inch which the weight, whose magnitude is known, has moved from its zero position. In order that specimens of different lengths may be tested in this machine, and that a specimen which is being tested may be free to vary its length to a small extent, the boss of the worm wheel consists of two parts, the boss itself and an inner sleeve, thus making the boss telescopic. The sleeve is free to move longitudinally in the boss, but is prevented from rotating with respect to it by a pair of feather keys. Two smaller sleeves are made use of to form the connection between the specimen and the larger sleeve, at one end, and the beam at the other.

An apparatus for taking an automatic record of the test is attached to the front of the beam. The diagram is drawn upon a sheet of paper attached to a brass disc. When the poise-weight is in its zero position, that is, when there is no moment on the specimen, the recording

pencil is at the centre of the disc. As the weight moves and the moment on the shaft is increased, the pencil is caused to move outwards in a radial direction, by means of a reducing mechanism, a distance proportional to, but less than, the distance traversed by the weight itself. The increase of twisting moment is accompanied by a torsional strain consisting of a rotation of the end of the specimen attached to the worm wheel with respect to the other end. The strain is recorded on the diagram by a rotation of the disc through the same angle as the shaft has been twisted through. This rotation is effected through a train of mechanism consisting of four equal spur wheels and a small counter shaft, connecting the worm wheel and the disc, it being assumed that the worm wheel rotates through exactly the same angle as the end of the shaft. There is an error here, but it may be considered negligible for the purpose for which the autographic diagram is to be used.

This particular machine will break in torsion circular steel shafts up to $\frac{3}{4}$ in. diameter.

For machines of this type, the specimen shafts are prepared with enlarged ends, as shown on Fig. 95. These enlarged ends are provided with pairs of keyways corresponding to the feather keys in the holders.

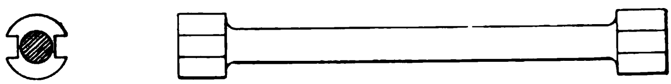


FIG. 95.—Wicksteed's Torsion Test Bar.

112. Torsion Attachments to Tension Testing Machines. On Fig. 26 is shown a photographic view of a small tension testing machine made by Messrs. Buckton, and it will be seen that there is a torsion arrangement very similar to one last described. The existence of this attachment does not in any way interfere with the use of the machine for tension purposes, but it is always there to be used when required.

Similar arrangements for torsional testing have recently been attached to some of the larger machines by the same makers. Among these may be mentioned the torsion attachment applied to the 100-ton tension machine at the Bradford Technical School. This is capable of taking specimens up to 2 in. in diameter and 12 in. long on the measured

portion, under a maximum twisting moment of 120,000 inch-pounds.

On Fig. 35, p. 86, will be seen the large worm wheel used for the torsion tests on Professor Elliot's machine, on the side of the lever remote from the observer.

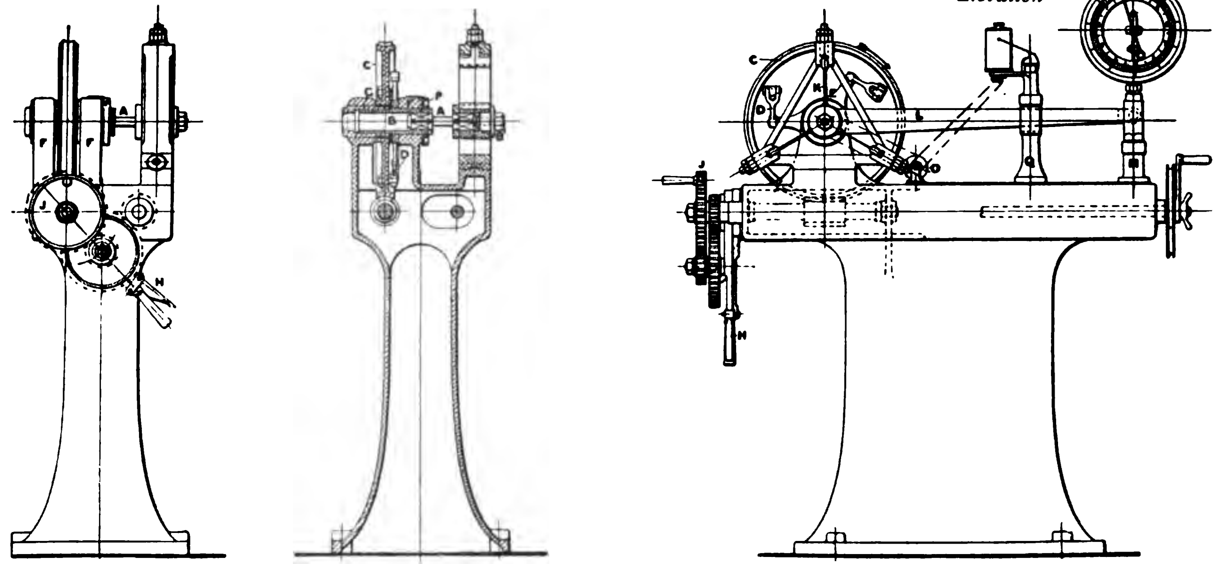
113. Messrs. Greenwood and Batley's Torsion Gear.—The machine illustrated on Fig. 30, p. 78, is in some cases provided (in addition to the appliances for testing in tension, compression, and bending) with additional gear to be used for carrying out torsional tests. On referring to this illustration, it will be noticed that there are two holes through the main bed of the machine. These form bearings wherein turn a pair of flanged wheels, these wheels carrying sockets in their centres for holding the two outer ends of a torsion specimen. Each of these wheels is provided with a chain attached to its rim and passing from the wheel horizontally and linked to the movable crosshead of the machine. By means of this piece of apparatus the outer ends of the apparatus are rotated together and the strain taken up. The middle portion of the specimen between the wheels is taken hold of by the lower end of a short vertical lever, the upper end of which is connected through a horizontal link with the system of weighing levers. The pull on the end of the twisting lever, and, therefore, the moment on the specimen, is measured in this way, the strain being taken up by moving the sliding crosshead outwards along the bed of the machine. The specimens tested in this machine are of necessity short.

The holes through the centres of the chain wheels are square in shape to receive the ends of the specimens, and they are also fitted with square dies having smaller square holes to receive specimens of smaller size.

114. Deeley Torsion Machine.*—This machine, invented by Mr. R. M. Deeley, is in use at the Midland Locomotive Works, at Derby, and possesses some novel features which are worth noticing. Three views of the machine are shown in the accompanying illustrations (Figs. 96, 97, and 98), an end elevation, a section, and a side elevation. In this machine, as before, one end of the specimen is held in the boss of a worm-wheel C, while the other is secured

* **Proceedings Institution of Mechanical Engineers, October, 1898. Mr. Peet's paper.**

End Elevation. *Transverse Section.* *Elevation*



FIGS. 96, 97, AND 98.—DEELEY'S TORSION TESTING MACHINE.

to the boss of a lever L. The test-bar is marked A. The specimens used are comparatively short ones. The great difference between this and the other torsion machines is in the arrangement of the measuring lever. Here, instead of having the lever resting on the knife edge, as is the usual practice, the hollow centre, which holds one end of the test bar and forms part of the lever, is held in position by what is in effect an elastic frictionless support. This consists of the three steel plates marked K on the side elevation above, attached to three corners of a triangular frame which is bolted to the bed plate. By holding the centre in this way, the lever is allowed to rotate through a very small angle, and be at the same time supported in position. The centre, which carries the other end of the test piece, instead of being rigidly attached to the worm wheel, is connected with it through three links, which are attached to the ends of a three-armed lever forming part of the centre, being rigidly keyed to it. This arrangement allows the necessary end play of the specimen.

The manner of measuring the twisting moment is rather unusual. Instead of having a moving jockey-weight, and estimating the moment as the product of this weight into its distance from its zero position, the moment is measured at a constant arm, and by means of a spring, as in a steam-engine indicator. This will be clearly seen in the illustration. The end of the lever presses upon a vertical rod which is attached to the lower end of a spring of known strength, and as the twist is put upon the test bar by means of the worm wheel, the outer end of the lever is pressed downwards and the spring is slightly extended, the actual amount of the strain being proportional to the downward force exerted by the lever end. The extent of the strain of the spring, and therefore of the twisting moment also, is indicated by the movement of a rotating pointer on the dial shown. The gauge is directly graduated by attaching a balanced lever to the elastic centre, and loading it to the moments required. The indications given are marked upon the dial, which is graduated so as to give the load in tons acting at an arm equal to the radius of the test bar used, 0·399 of an inch. This value can be reduced to any other terms as may be wished. The standard size of test bar used in this machine is shown on Fig. 99, the diameter being arranged to give a cross section of one-half a square inch.

An autographic diagram may be drawn by means of the

Crosby indicator, shown in the illustration. When an autographic diagram is to be taken the lever is so arranged that it compresses the spring of the indicator as it descends, the amount of the compression being proportional to the moment on the bar. This is accompanied by a movement

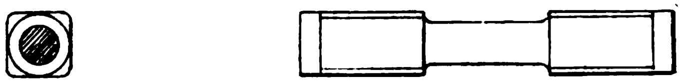


FIG. 99.—Deeley's Torsion Test Piece.

of the pencil, which is of necessity also proportional to the moment. The horizontal motion of the paper drum is effected by a cord connection with the centre, which holds the worm-wheel end of the specimen, and the horizontal movement of the paper is proportional to the angular twist of the specimen.

115. Riehlé Bros. Torsional Testing Machine.—Messrs. Riehlé Bros., of Philadelphia, make a torsion testing machine of large power, which has some novel details worth considering. The machine consists essentially of two headstocks, which serve to carry the centres in which the ends of the test specimen are held. One of these, carrying the centre at which the moment on the bar is measured, is fixed upon the bedplate of the machine, while the other one, carrying the worm-wheel, is capable of being moved along the bed, so that the length of the specimen can be varied. This longitudinal movement is effected by means of a rack and pinion. The twisting moment is determined by having two arms instead of one in the more usual arrangement. These two arms project from the grip-head horizontally on opposite sides, and, by means of an equalising lever below the centre, two equal moments are imposed on opposite sides of the centre. The end of this lever is linked to the knife-edge at the end of the short arm of a second horizontal lever. The end of this again is connected by a vertical link to the short arm of the third lever. This third lever carries the jockey-weight, whose position on the lever serves to indicate the twisting moment on the specimen. So that, in this machine, the moment is applied through a system of three levers instead of one, making the actual weights to be dealt with much smaller, and rendering the manipulation of the machine easier. The graduations on the weighing lever are so arranged that the

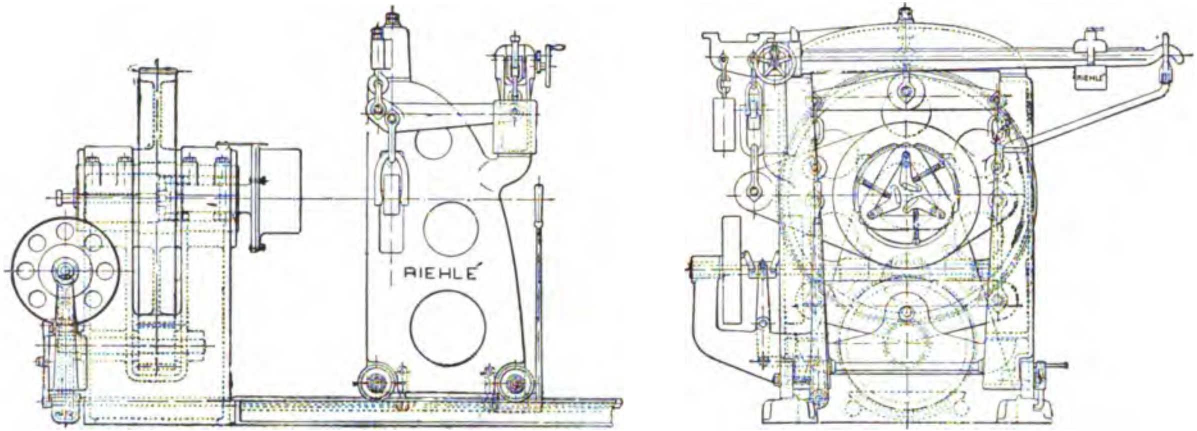


FIG. 100.—MESSRS. RIEHLE'S IMPROVED FORM OF TORSIONAL TESTING MACHINE.

moment is recorded in foot-pounds directly without any calculation. The specimens used in this machine are made with square ends, and are held in a self-centering grip.

The twist is put upon the specimen through a power-driven speed cone working on to a train of gearing. Specimens up to 1½ in. diameter and 20 in. long can be tested in this machine. The longitudinal movement of the loose headstock is up to 12 in. There is a graduated circular scale attached to the loose headstock by means of which the angle twisted through by the specimen under test is indicated.

The accompanying illustration, Fig. 100, represents an improved form of torsion machine made by Messrs. Riehlé. This machine is capable of applying a twisting moment of 250,000 inch-pounds. The power is applied through a system of compound levers, and the end of specimen at which the twisting moment is applied is held in a set of toggle grips, supported by a parallel system of levers, which arrangement completely neutralises any stress except that exerted by the specimen. Specimens up to 10 ft. long can be tested in this machine.

116. Observations on Torsional Testing Machines.—From the above descriptions it will be gathered that there is considerable variety in the arrangement of torsional testing machines. Many of the details are defective. In all probability the best arrangement for the measurement of the twisting moment is that of a simple lever carrying a constant load whose position can be varied. This is the most convenient method, besides being more accurate than using a constant arm and spring instead of a deadweight. Whatever the magnitude of the jockey weight it can be perfectly balanced in its zero position by means of a counter-weight, its movement along the arm can be measured with a great degree of accuracy, and the weight itself, when once it is standardised, remains practically invariable. A spring, such as the one that would be used to take the place of a deadweight, besides depending for its readings on a previous calibration with known weights, may possibly become affected by constant use, and the value of its readings changed; and, if this does happen, there is nothing to indicate that an error has arisen. A compound lever arrangement, such as the one used on the Riehlé machine, makes it possible to use small weights and renders the

manipulation easier, and this is especially true of large specimens, but it lacks the most important desideratum—simplicity. Any multiplication of parts only adds to the possibilities of error, and makes such errors as do exist more difficult to detect.

The method of supporting the specimen in Deeley's machine appears to be good, both in the provision made for allowing a longitudinal variation in the specimen, and in the frictionless support at the lever end. Of course this latter arrangement only admits of a very limited angular movement of the lever, and makes very delicate handling necessary if a weight is used in place of the spring.

117. The Measurement of Torsional Strains.—Some of the principles which should be observed in taking measurements of the longitudinal strains of test bars in tension are equally applicable to the measurement of torsional strains. In the first place, the measuring apparatus should, if possible, be attached to, and carried by, the bar itself, so that the actual relative rotation of one cross-section of the bar with respect to some other, may be measured. The observation of this rule is absolutely necessary when only the elastic strains are to be determined. In some torsion machines the plan is adopted of observing the relative movement of the parts of the machine which hold the two ends, and, assuming this to be the same as the twist of the shaft itself; this cannot be done without introducing an error, because the mechanism of the machine and the holding bushes and keys must undergo a certain amount of deformation themselves, and this is, of course, registered as a strain of the specimen. If the worm wheel and its fittings are of heavy design, and accurately made, and care is taken that all backlash is eliminated before any observations are made, the error due to the deformation of the machine will be small compared with the strain of the specimen itself.

For strains *beyond* the limit and for the rougher kind of tests this method of strain measurement may be safely employed, but for elastic strains it is desirable to take the measurement from the shaft itself, and not from any piece of the machine to which it may be attached.

The author* has made use of the above method in making a series of tests of solid and hollow shafts of the

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* Popplewell and Coker on Shafts. Proceedings of Institution of Civil Engineers, vol. cxxii.

same nominal strength. The errors caused by the deformation of the machine were found to be extremely small. The machine used in these tests was one of Mr. Wicksteed's small torsion machines similar to that shown in Fig. 94. Here the handwheel used for rotating the worm was divided into 24 equal arcs, each equivalent to 10 minutes, as the worm wheel had 90 teeth.

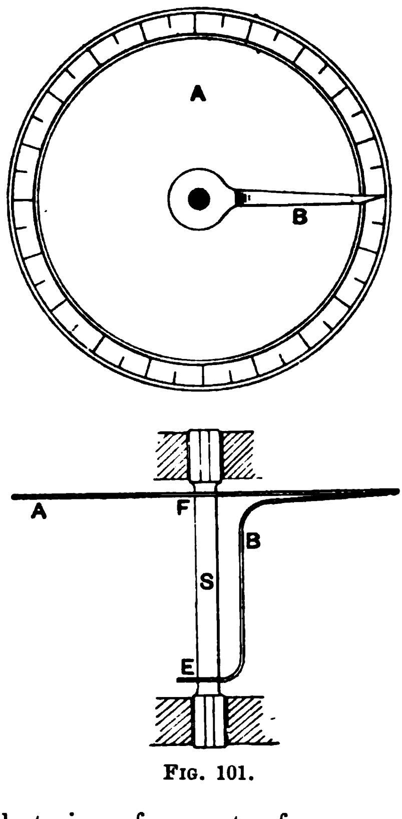


FIG. 101.

The simplest piece of apparatus for measuring torsional strains directly is an arrangement similar to that indicated by the diagram on Fig. 101. Here S is the specimen which is being twisted, and whose angle of twist it is required to measure. This measurement is made on a certain definite length of the parallel part of the bar E F. A graduated disc or sector A is fixed to one end of this length, and a radial pointer B

to the other, and, as the shaft twists under the stress imposed, these two move with respect to one another; that is to say, the pointer moves over the graduated arc and traces out the angle of twist. The larger the diameter of the graduated circle, of course, the more precise will be the readings which it is possible to obtain. Suppose that the smallest linear measurement which can be conveniently read by direct means to be $\frac{1}{100}$th of an inch, and the radius of the pointer to be 20 in.; this one-hundredth of an inch at the circumference corresponds to an angle of 0·03 of a degree.

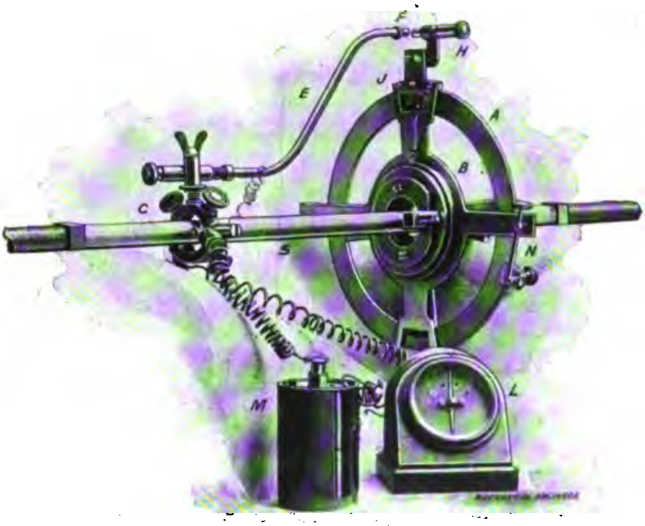


Fig. 102.—Coker's Screw Micrometer Instrument for Measuring Torsional Strains.

In their experiments on the torsional strength of shafts, Messrs. Platt and Hayward made use of beams of light reflected from two mirrors, instead of material arms. Unfortunately the details of the apparatus employed are not given in the paper describing the experiments.*

118. Coker's Instruments for Measuring Small Torsional Strains.—Two instruments of greater delicacy than those described have been designed by Mr. Coker, of Mc.Gill University.

The former of these is shown on Fig. 102. The shaft

* Proceedings of Institution Civil Engineers, vol. xc

whose torsional strains are to be measured is marked S. On one end of the length to be measured is attached the graduated circle A, through a chuck plate B, which is itself attached to the specimen by means of the three centering screws adjustable by hand. At the other end of the measuring portion is attached the arm E, which works on a swivel joint carried by the ring C. This ring has also adjusting screws with which to fix it to the shaft. The arm E terminates in a contact ball F, which can be brought into contact with the end of the micrometer screw H, which is mounted on a vernier plate J. This can be clamped in any position on the graduated circle, the fine adjustment

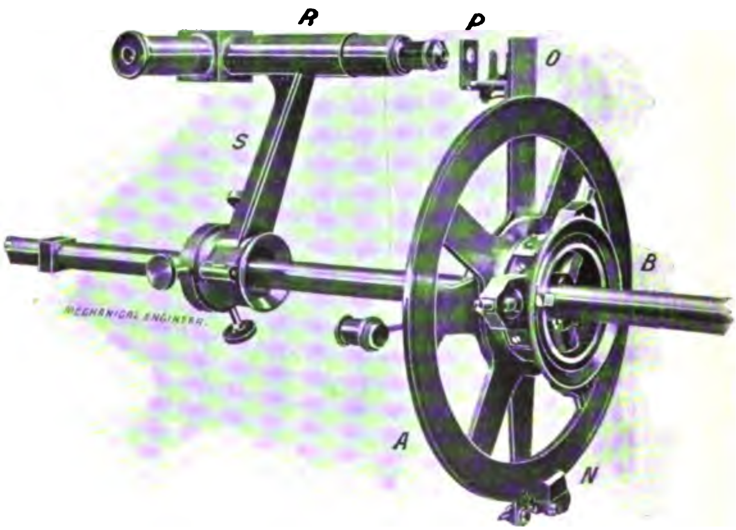


FIG. 103.—Coker's Microscope Torsional Measuring Instrument.

being made with the tangent screw N. A cell and galvanometer, M and L, are joined in circuit through the bar, so that when the ball F is in contact with the screw H the circuit is completed, and the galvanometer needle is deflected.

The instrument is used in the following way: The contacting pieces being supposed to be touching, a twisting moment applied to the bar will separate these pieces, and the circuit be broken. The micrometer screw must now be advanced until the circuit is again completed, as shown

by the deflection of the needle. The number of divisions through which the screw has been turned affords a measure of the angular twist of the bar. The actual value of the angle corresponding to a division of the micrometer screw is determined in the first place by means of the graduations on the circle and the vernier. It will be noticed that, as the micrometer screw moves tangentially, its readings are not strictly proportional to the angles, but to the tangents of these angles; but for small angles the errors involved are very small, and may be neglected as compared with the quantities under measurement. In the case of the particular instrument described by Mr. Coker, the mean of the calibration tests gave 18·6 divisions of the micrometer screw as corresponding to one minute of arc, or, in other words, one division of the micrometer screw is equivalent to about one-thousandth of a degree. It will be seen that the accuracy of the readings is dependent upon the accuracy of the making and calibration of the micrometer screw.

A second instrument of greater precision is shown on Fig. 103. Here the micrometer screw and electrical apparatus are replaced by a reading microscope, which is made use of much in the same way as the one in Professor Ewing's extensometer (see p. 118 *ante*). As in the last instrument, one end of the measured portion of the bar carries a graduated circle, whose attachment is made through a self-centering chuck of somewhat novel form, by means of which the centre of the graduated circle is made to automatically coincide with the centre of the test-bar. In this instrument the graduated circle is at A, the chuck B, the vernier plate N carrying a radial arm O, from which projects an arm carrying the wire P upon which the readings are taken.

At the other end of the bar is attached an arm S, by means of three centering screws; and, at the extremity of this arm is carried a reading microscope, R, by means of which the readings are taken. For convenience in reading, the eye-piece of this microscope is placed at right angles to the main tube, and a right-angled prism is interposed between the objective and the eye-piece. A graduated glass scale is placed in the focus of the eye-piece. The calibration of the instrument is effected by moving the wire upon which the readings are taken through a definite angle of ten minutes, and noting the equivalent reading of the micrometer eye-piece. In the particular instrument described by Mr. Coker it was found

that the calibration test gave 36 divisions of the scale as corresponding to one minute of arc. Angular displacements of one second of arc can be measured with this instrument.

On Fig. 104 is shown a most important attachment to this instrument. This is the clamp used when putting the instrument on the test bar. Its object is to fix the apparatus on the bar with its plane accurately perpendicular to the axis of the bar, and its centre coinciding with the axis. This clamp consists of a pair of divided collars, the halves of which are pivoted together and secured by nuts. The

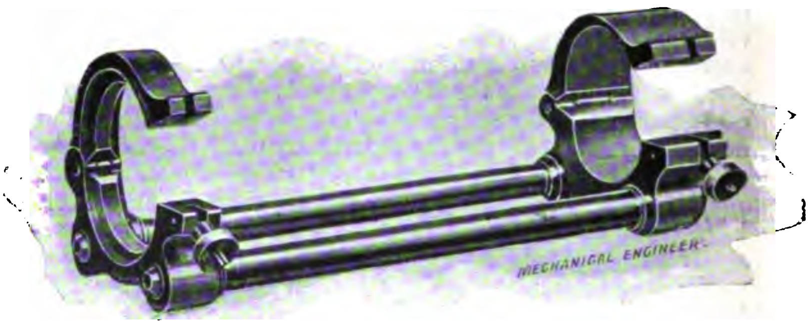


FIG. 104.- Fixing Clamp.

collars are wedge-shaped in radial section to engage with corresponding wedge-angled grooves upon the chuck plate and cylinder. The lower halves of the divided collars are connected by one or more distance pieces. When using the clamp, the two parts of the instrument are clamped together and so held rigidly in the proper position, and then the test bar is inserted and the gripping screws tightened, when the clamp may be removed, leaving the two main pieces accurately spaced on the bar, while the graduated circle remains perpendicular thereto, and very approximately centred.*

119. Example of a Complete Test of a Mild Steel Bar in Torsion.—The following is an example of a test under torsional stress carried out on a turned bar of mild steel. This bar was made with enlarged ends, and fitted with keys, by means of which it was held in a torsion machine of the kind illustrated on Fig. 94. After carefully measuring

* "Instruments for Measuring Small Torsional Strains." British Association, 1898.

the diameter of the bar with a vernier calliper, it was placed in the machine and the beam balanced with the poise weight set to zero. The instrument used for measuring the angular deflections was next fixed in its place on the bar, the distance between the two halves being 8 in., this constituting the portion of the bar whose strains were measured. When the test was begun, the pointer of the measuring instrument was set to zero, and the twisting moment on the bar varied by increments of 25 inch-pounds up to the elastic limit, and increments of 50 inch-pounds beyond this point. The position of a known point on a hand wheel was also noted at the start, so that, by counting its revolutions and parts of a revolution, it was possible to measure the angles of twist beyond the elastic limit. Below is a table of the actual readings taken:—

RECORD OF TORSION TEST ON MILD STEEL BAR.

Diameter of Bar, 0·472 in.; Length of Measured Portion, 8 in.

Twisting Moment. Inch-pounds.	Angle of Twist. Degrees.	Twisting Moment. Inch-pounds.	Angle of Twist. Degrees.
50	0·30	500	85
75	0·52	550	112
100	0·73	600	144
125	0·91	650	181
150	1·13	700	221
175	1·33	750	266
200	1·55	800	318
225	1·74	850	398
250	1·95	900	485
275	2·16	950	590
300	2·38	1000	722
325	2·57	1050	892
350	2·75	1100	1085
375	2·93	1150	1400
400	3·12	1200	1725
425	3·30	1250	2102
450	3·50	1300	2540
475	3·70	1348	3480*

* At this point fracture occurred.

Taking the readings up to 450 inch-pounds, the differences per 225 inch-pounds are—

3·50	3·30	3·12	2·93	2·75	2·57	2·38	2·16
1·74	1·55	1·33	1·13	0·91	0·73	0·52	0·30
1·76	1·75	1·79	1·80	1·84	1·84	1·86	1·86

The mean of these is—

$$\begin{array}{r} 1 \cdot 76 \\ 1 \cdot 75 \\ 1 \cdot 79 \\ 1 \cdot 80 \\ 1 \cdot 84 \\ 1 \cdot 84 \\ 1 \cdot 86 \\ 1 \cdot 86 \\ \hline 8)14 \cdot 50 \\ \hline 1 \cdot 8125 \\ \hline \end{array} \left\{ \begin{array}{l} \text{degrees for each 225 inch-pounds} \\ \text{of twisting moment.} \end{array} \right.$$

Making use of the formula already mentioned, on page 46, the Modulus of Rigidity is—

$$G = \frac{5760 \, . \, l \, . \, T}{\pi^2 . \, a . \, d^4}$$

In the present case

$$\begin{aligned} l &= 8 \text{ in.} \\ T &= 225 \text{ inch-pounds.} \\ \pi &= 3 \cdot 1416 \\ a &= 1 \cdot 8125 \text{ degrees} \\ d &= 0 \cdot 472 \text{ in. diameter.} \end{aligned}$$

Putting in these values,

$$\begin{aligned} G &= \frac{5760 \, . \, 8 \, . \, 225}{(3 \cdot 1416)^2 \, . \, 1 \cdot 8125 \, . \, (0 \cdot 472)^4} \\ &= 11{,}800{,}000 \text{ lbs. per square inch.} \\ &= 5{,}225 \text{ tons per square inch.} \end{aligned}$$

The value of the modulus of direct elasticity for mild steel is somewhere about 30,000,000 lb. per square inch; in the example given on a former page it was found to be 28,860,000 lb. per square inch. It has been shown (page 20) that, reasoning from purely theoretical considerations, the ratio of the modulus of rigidity, G, to the modulus of direct elasticity, E, is as 2 to 5, or

$$\frac{G}{E} = \frac{2}{5} = 0 \cdot 400$$

Now, taking the values found in the two cases quoted,

$$\begin{aligned} G &= 11{,}800{,}000, \text{ and} \\ E &= 28{,}860{,}000, \end{aligned}$$

So that the ratio

$$\frac{G}{E} = \frac{11{,}800{,}000}{28{,}860{,}000} = 0 \cdot 409$$

This result is, of course, only an approximate demonstration of the truth of the fact that G : E : : 2 : 5 for the same material. The two tests were not made on steel from the same piece, but the two metals were of very similar character.

When the shaft is still elastic, the shearing stress at any point on a section of the bar is directly proportional to the radial distance of this point from the axis, and, therefore, the maximum stress is always at the outer surface. On this account it is these outer layers that are first strained beyond the elastic limit, while the layers nearer the axis are still in the elastic state. When once these outer layers begin to take permanent set, a greater stress is thrown on those layers coming next to them, and so on, the semi-plastic condition gradually penetrating inwards until the whole bar is in this state.

It will be readily understood that the commonly accepted formula for torsion,

$$T = \frac{\pi}{16} f_s d^3$$

is only true so long as the elastic condition is maintained, that is, so long as the stress is proportional to the distance from the axis.

The further the test progresses, and the nearer the point of fracture is approached, the more nearly is the truly plastic condition approximated to. As was pointed out (par. 16) a significant fact about the plastic condition, so far as a torsion specimen is concerned, is that under this condition the shearing stress at any point in a bar is not proportional to the distance of that point from the axis of the bar, but is sensibly uniform over the whole section of the bar; and the relations of stress and moment are now expressed by the formula (XXX.), instead of (IX.). This formula, which has already been given, is

$$T = \frac{\pi}{12} f_s d^3$$

Between the elastic limit and the maximum twisting moment, the relations of stress are not expressed by either of the two above formulæ, but probably by an expression of the form,

$$T = \frac{\pi}{x} f_s d^3$$

where f_s is the maximum shearing stress, and x has a value somewhere between 16 and 12.

120. Stress at the Elastic Limit.—In the above test, the elastic limit may be said to have been passed at a twisting moment of 500 inch-pounds. The formula—

$$T = \frac{\pi}{16} f_s d^3$$

may be taken as being true up to the elastic limit.

Putting this in another form, we have

$$f_s = \frac{16 \cdot T}{\pi \, d^3}$$

$$= \frac{16 \quad . \quad 500}{3{\cdot}1416 \;.\; (0{\cdot}472)^3}$$

$$= 24{,}300 \text{ lb. per square inch,}$$

$$= 10{\cdot}82 \text{ tons per square inch.}$$

The maximum twisting moment was 1,348 inch-pounds Owing to the fact which has already been referred to, namely, that near the point of fracture for a ductile metal the stress is nearly uniform over the section, the second formula must be employed :—

$$T = \frac{\pi}{12} \cdot f_s d^3$$

from which

$$f_s = \frac{12 \cdot T}{\pi \, d^3}$$

$$= \frac{12 \;.\; 1348}{3{\cdot}1416 \;.\; (0{\cdot}472)^3}$$

$$= 49{,}000 \text{ lb. per square inch.}$$

$$= 21{\cdot}85 \text{ tons per square inch.}$$

The shearing stress for the same metal, as obtained from direct shearing tests, is about 22·40 tons per square inch. There is, therefore, no very great difference between the two results, thus showing that it is right to assume the condition of uniformity of stress at the maximum twisting moment.

121. Diagram Plotted from the Torsion Test.—A graphical representation of the results of this test is given on Fig. 105. Here the twisting moments are plotted horizontally as abscissæ, and the corresponding angular deflections

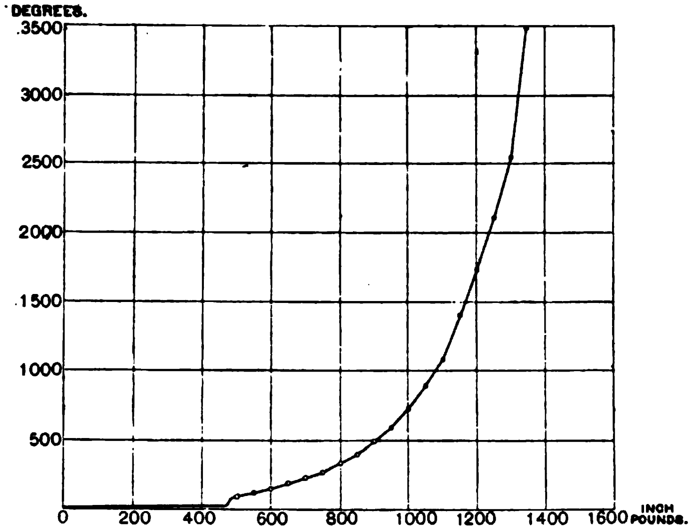


FIG. 105. — Diagram of Torsional Test of Mild Steel Bar 0·472 in. diameter and 8 in. long, showing twisting moments and corresponding angles of twist.

vertically upwards as ordinates. The general form of the curve obtained is not unlike the tension curve for the same metal. It will be seen that there is an elastic portion which nearly coincides with the base line for the scale used, a distinct step at the elastic limit, and an upward curve from this point. The curve for wrought-iron is very similar, while that for cast-iron is like the one for tension, being approximately a straight line to begin with, and gradually merging into slightly upward curve.

122. Fractures for Torsion Specimens.—The fractures for the more ductile materials, when tested to destruction in torsion, take place roughly on planes at right-angles to the axes of the specimens. Actual fracture occurs without any violence, and there is nothing very characteristic about the broken surfaces.

The form of the fracture in the case of the brittle materials, such as cast iron, is usually an almost perfect spiral, making an angle of 45 deg. with the axis of the bar, the spiral portion of the fracture making a complete revolution of the bar, that is to say, one whole pitch, and a remaining part being roughly a straight line joining the two ends of the spiral. This is the case in both solid and hollow bars.

In bars of ductile materials, especially in hollow bars of fibrous metals such as wrought iron, the axis of the bar and the whole bar itself often tends to assume a spiral or cork-screw shape before fracture takes place.

Chapter VII.

TESTING OPERATIONS—(*Continued.*)

APPLIANCES FOR DRAWING AUTOGRAPHIC DIAGRAMS.

123. In the examples of tests which have been quoted—that is to say, the tests in tension, compression, bending, and torsion—it has been shown that the results of these tests may be recorded or expressed graphically as well as by means of written figures. This is done in most cases by making use of rectangular co-ordinates, and plotting a curve whose abscissæ represent loads, and whose corresponding ordinates represent to some scale the strains of the test specimen produced by the loads in question. A curve of this kind has been called a load-strain diagram, and forms a very ready means of recording a test in a form which conveys to the mind an idea of the test much more rapidly than by inspecting columns of figures.

In these examples the stresses and their corresponding strains were measured at frequent intervals, and plotted afterwards. Attempts have been made, with more or less success, to provide means whereby the diagram can be drawn, as the test proceeds, by an appliance attached to the specimen itself. A diagram drawn in this way is called an "autographic" or "automatic" diagram.

It is exceedingly difficult to design a really satisfactory and accurate autographic apparatus. Let us see what are the principal conditions which have to be satisfied in doing this. First, take a simple tension test. It is required to be able to draw a curve whose abscissæ represent, say, the loads on the specimen, and whose ordinates represent the extensions produced by the corresponding stresses. It is the usual, but not invariable, custom to arrange the appliance so that the diagram is drawn upon a sheet of paper. In all cases the pencil which is to trace out the curve must have two independent movements with respect to the paper, one controlled by the load and the other by the strain of the specimen. Generally, these two movements are at right angles to one another.

Of these two movements, the one representing the strain of the specimen is taken direct from the specimen, and exactly corresponds to the relative movement of two fixed points on the bar, either as this movement actually exists or in a magnified form ; where the elastic extensions of a bar are to be recorded, a system of levers is interposed between the specimen and the pencil carriage. This strain movement is not difficult to arrange for, but, unfortunately, the same cannot be said of the stress movement. In the great majority of tension machines the observer obtains his information as to the load on the specimen at any moment from the position of a known weight on the weighing lever. A pointer attached to this weight travels along a scale attached to the beam, and the load on the specimen is in this way indicated. The weak point about this is that the reading is only true so long as the beam is floating freely between its stops ; if the beam rests on one of the stops the indication is rendered

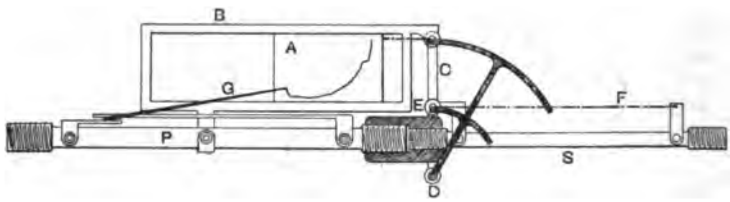


Fig. 106.—Kennedy's Apparatus for Drawing Autographic Diagrams.

useless. But a man who is in the habit of manipulating a testing machine is fully aware of this and is accordingly careful to keep his lever always floating when taking readings. In some forms of autographic apparatus the load movement of the pencil is controlled by the movement of the jockey weight, and is, in fact, a *facsimile*, on a reduced scale, of its motion, the reduction being effected by a system of tooth gearing or pulleys. An arrangement of this kind only produces a semi-autographic diagram because the accuracy of the load movement of the pencil depends on the care and skill with which the machine is manipulated. A truly autographic apparatus must draw a diagram quite independently of the observer who is controlling the machine.

124. Dr. Kennedy's Apparatus.—This appliance may be taken as representing one of the most successful attempts to

produce an apparatus capable of drawing accurate and purely autographic diagrams of tension tests. This piece of apparatus is represented diagrammatically on Fig. 106. It consists essentially of two parts, namely, the strain recording portion and that for recording the stress. The diagram is drawn upon a sheet of smoked glass at A. This glass slides in a frame B, which is attached to the middle of the "spring-piece" P. This frame also carries the centre about which the radial arm, C, rotates. On the end, D, of this arm rotates a frame consisting of an arm and two pieces forming arcs of circles whose radii are in the ratio of 1 to 2. Around the arc having the smaller radius passes a wire, or its equivalent in the form of a strip of steel. The other end of this is attached to the further end of the specimen. To the arc of larger radius is fastened a thread which itself is attached to the sliding frame carrying the sheet of smoked glass upon which the diagram is to be drawn. The mode of operation of this part of the apparatus is as follows: The test specimen, S, stretches under the load, and the two points at which are respectively linked to the arm C and E, and the free end of the wire F, move with respect to one another. The result is that the wire is pulled, and the radial arm rotated through a small arc, and, consequently, the thread which is fastened to the slide is moved through twice the distance represented by the stretch of the specimen. This constitutes the movement necessary to record the strain, the movement of the sheet of glass being proportional to, but double, the extension of the bar.

In order to obtain the other co-ordinate of the diagram, a special piece of apparatus is interposed between the shackles of the machine and the specimen. To this has been given the name of "spring-piece." By making use of this, the load on the specimen at any moment is recorded in a manner which is entirely independent of the lever of the machine and its poise weight. This spring piece is simply a test piece of larger size than the one which is being tested, its size being such that the maximum load on the specimen does not stretch it beyond its elastic limit. As the spring piece, P, and the specimen, S, are placed "in series," any load which comes upon the specimen has to be transmitted to it through the spring-piece, which itself sustains precisely the same load. In consequence of the spring piece at all times carrying stresses which bear a fixed ratio to the stresses on the

specimen, and the elastic stretch of spring piece being proportional to the load upon it, it follows that this stretch is a direct measure of the load upon the specimen. This fact is taken advantage of in the working of the apparatus.

The spring piece is made of such dimensions and material that the maximum loads on the specimens which are tested never approach its elastic limit. The pointer G, which is used to draw the diagram, is carried by a small roller forming its centre of rotation. This roller lies between and is pressed upon by two plates, one of which is attached to each end of the spring piece. As the spring piece stretches under the load the two plates move with respect to one another, with the result that the roller is rotated, and with it the pointer. The rotation of the index, and therefore the circumferential movement of its point, as it traces out the diagram on the glass, is a measure of the stretch of the spring piece. This is a measure of the load upon the spring piece, and therefore of the load upon the specimen also. A large magnification of the stretch of the spring piece is obtained by the large ratio which the arm of the pointer bears to the radius of its roller. By carefully selecting the spring piece, the load can be made exactly proportional to the circumferential movement of the pointer, and by direct calibration with actual loads in the testing machine, the movement of the pointer which corresponds to given load can be ascertained.

It is only necessary, then, after adjusting the apparatus, to go on increasing the load upon the specimen until fracture takes place, and the whole history of the process, as regards relation of stretch to load, will be told upon the smoked glass by the specimen itself. When the diagram is completed it is varnished and used as a negative, from which photographic prints may be taken.

This instrument is truly automatic, and is quite independent of any outside manipulation, but at the same time it possesses several disadvantages which militate against its general use. One of these is that the load movement of the pointer is in a circumferential direction instead of being in a straight line at right angles to the direction of the stretch movement. For many purposes this matters little, but where the diagrams have to be compared with the diagrams plotted from rectangular coordinates a somewhat tedious process of reduction is necessary.

The existence of the spring-piece adds to the complication of the testing apparatus, and a second holding device has to be provided at the end of the spring-piece nearest the specimen. Any slip or yielding of the specimen in the grips would, under ordinary conditions, be included in the movement representing the stretch of the specimen, but this difficulty is obviated by the use of the differential arrangement of the pulleys which serve to transmit the elongation. So far as the writer is aware, this apparatus has only been used with specimens having specially turned heads, and no attempts have been made to use it with ordinary wedge grips.*

125. Wicksteed's Autographic Recorder.—In order to produce workable autographic diagrams without the employment of so delicate an instrument as that of Dr. Kennedy, Mr. Wicksteed has designed an apparatus on very different lines. A very good idea of the general appearance of this instrument will be obtained from the illustration on Figs. 21 and 22. Here the autographic apparatus will be seen standing in the space below the beam of the machine, and having somewhat of the appearance of a small lathe. An enlarged view of the more important details is given in plan and longitudinal section in Fig. 107. The diagram itself is drawn upon a sheet of paper fixed upon the surface of a drum, D. The rotational movement of this drum is produced by the stretch of the specimen, the motion being transmitted by means of a fine wire, one end of which is attached to the lower end of the specimen, after passing over a small pulley fixed to a clip on the upper end, so that, as the bar stretches, the wire is drawn over the pulley to an equal extent, and the drum is in this way rotated. It will be seen that the wire, before reaching the instrument, passes over two other guide pulleys, placed at the joints of a light wooden knee-frame. This arrangement has been adopted in order to prevent any movement of the specimen, due to the slipping of the holding wedges or the swing of the beam, being recorded as a part of the strain. The wire, after passing round the drum pulley, is kept tight by means of a small weight.

It is in his method of recording the load upon the specimen that Mr. Wicksteed makes use of a somewhat novel arrangement. In most testing machines the strain

* This instrument will be found to be fully described in the Proc. Inst. Mech. Eng., 1886, p. 65.

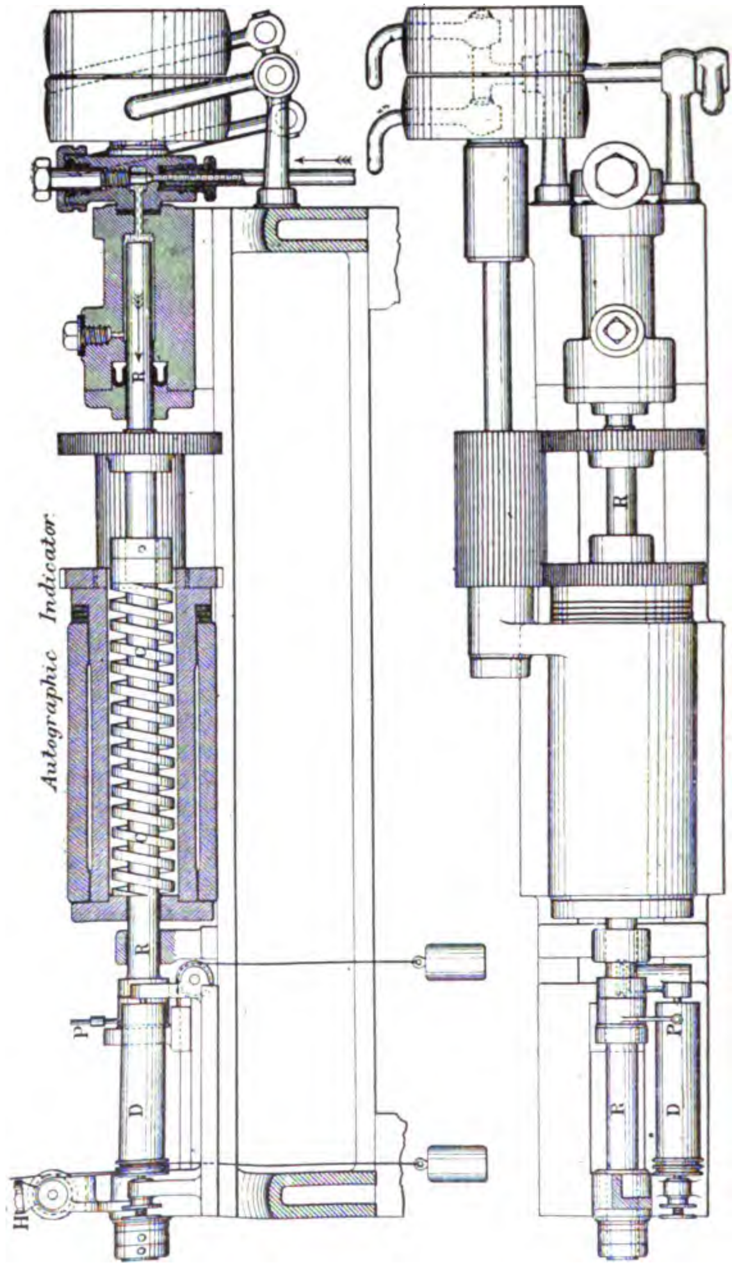


FIG. 107.—LONGITUDINAL SECTION AND PLAN OF WICKSTEED'S AUTOGRAPHIC RECORDER.*

* Taken from Inst. Mech. Eng. Proc., 1886.

is taken up and the load applied by the pressure of water upon an hydraulic piston or ram. Consequently the load upon the specimen is at all times sensibly proportional to the intensity of the pressure of the water in the ram cylinder, whatever be the position of the poise weight on the weighing beam, and no matter whether the beam be resting on its upper or lower stop. In the present instrument advantage is taken of this principle, and the indications of the loads on the specimen are made to depend upon the water pressure in the ram cylinder. The pressure is communicated to the ram of a small cylinder by a pipe leading from the main cylinder. The miniature ram is shown at R in the figure, and is made to press against a spiral spring, C. The continuation of the ram beyond the spring carries the pencil with which the diagram is drawn.

As the load on the specimen increases, the water pressure in the main cylinder increases in the same ratio, and, as the pressure is the same in the cylinder of the instrument, the pressure upon the small ram is proportional to the load on the specimen. As the load comes upon the small ram, it compresses the spring and moves the pencil. The compression of this spiral spring is proportional to the load producing the compression; therefore we have the final result that the movement of the pencil from its zero position is proportional to the load on the specimen at any moment. This is only true within certain limits.

Besides small variations of load due to the inertia of the moving parts of the machine which may be unrecorded, there is an error caused by the friction of the packing of the main ram; that is to say, the water pressure on the ram is balanced, not only by the load on the specimen, but by this added to the friction of the ram. It has been found experimentally that the ram friction is sensibly proportional to the total load on the ram, and therefore the presence of this will not affect the general form of the diagram produced, but only its scale.

The scale of the diagram can be determined experimentally by comparing the readings with actual observations of the beam scale, and this calibration can be checked from time to time. Besides the friction of the ram packing the water pressure has also to overcome the friction of the crosshead slides, and, as this is a somewhat variable quantity, another source of error is thereby

introduced. What is most unsatisfactory about the effect of the ram friction on the scale is due to the fact that this friction acts sometimes with the load, and sometimes against it; and, consequently, the friction may be a plus quantity at one point of test, and a minus one at another. But this hardly affects an ordinary test, where the strain is continuous in one direction.

As there is a frictional force between the main ram and its packing, so there is also the small amount of friction between the ram of the instrument and its packing, which, if not obviated, would considerably interfere with the movement of the pencil. Mr. Wicksteed has, however, resorted to the very ingenious plan of rotating the ram continuously by means of belt gearing driven from the main shafting, and thereby reducing the frictional resistance to motion to a minimum.

126. Semi-Automatic Recording Apparatus.—The two pieces of apparatus which have so far been dealt with may be described as truly automatic in their working, that is to say, they are independent of those parts of the testing machine which are used to control the load upon the specimen. In the case of either of these appliances, if the poise-weight were never moved from its initial position on the weighing lever, but the specimen were to be broken by the application of the hydraulic pressure with the beam fixed against its upper stop, precisely the same diagram would be drawn as if the beam had been kept floating during the whole of the test.

In the examples next to be described, the case is different. In all these the strain movement is, as before, taken direct, in its original or magnified form, from the specimen. The load movement of the pencil is made to depend on the position of the poise-weight, from which it takes its motion. In a test as ordinarily carried out, the load on the specimen at any moment is given by the position of the jockey-weight on its beam, the actual reading being taken on a graduated scale, along which moves a pointer or vernier. This is the only means of ascertaining the load upon a bar, and it must be remembered that it is accurate only so long as the beam is in equilibrium and floating freely between its stops. Assuming therefore that the beam is always floating, then, if the pencil of the autographic apparatus is made to move from its original position a distance always bearing a constant ratio to

the simultaneous movement of the weight, this distance moved by the pencil will be a measure of the load upon the specimen, to a certain scale. This is the plan which is adopted in all instruments of the present class.

Among these are the instrument of Professor Unwin, and a number of others very similar in principle, such as those of Mr. Aspinall, Professor Hele-Shaw, and Professor Hearson; there are also a number of Continental and American designs based essentially on the same principles.

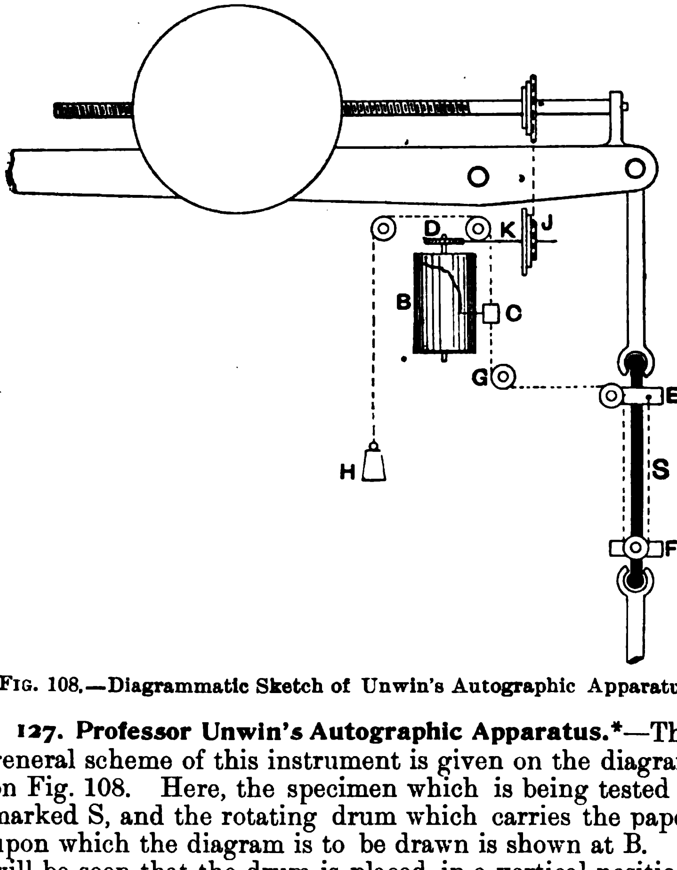


FIG. 108.—Diagrammatic Sketch of Unwin's Autographic Apparatus.

127. Professor Unwin's Autographic Apparatus.*—The general scheme of this instrument is given on the diagram on Fig. 108. Here, the specimen which is being tested is marked S, and the rotating drum which carries the paper upon which the diagram is to be drawn is shown at B. It will be seen that the drum is placed in a vertical position, and rotates on a spindle which terminates in a worm wheel at D. Upon the drum is fixed a sheet of paper, and the

* See Unwin's "Testing," p. 236.

diagram is drawn by a pencil C. This pencil is attached to a small carriage which slides up and down two guide rods, and whose motion is made to depend upon the stretch of the specimen. Two clips, E and F, are fixed to the top and bottom of the specimen respectively, and are such that they are perfectly rigid on the bar. To the lower of these is fixed a small pulley, and to the upper one the fine wire used to transmit the motion is attached. This wire is led downwards over the pulley at the lower end of the specimen, and upwards again, passing over a pulley on the top clip; from here it is led horizontally to the guide pulley G, and thence direct to the pencil carriage of the instrument. The wire is kept tight by means of the weight H. From this it will be seen that the elongation of the specimen is magnified two-fold before it is transmitted to the pencil. By leading off the wire horizontally as shown, and parallel to the knife edge, any error that might arise from the movement of the specimen as a whole is reduced to a negligible quantity.

The indications of the loads on the specimen are made in a direction at right angles to that of the extension by the rotation of the drum. The machines to which this apparatus has been applied are of the single-lever type, in which the movement of the poise-weight is controlled by means of a screw, and the motion of the weight, and therefore of the load on the specimen also, is proportional to the rotation of this screw, and this fact is taken advantage of in the working of the instrument. The motion of the beam screw is transmitted to the small grooved pulley J by means of a catgut band. On the same spindle as the grooved pulley is a worm which gears into the worm wheel of the paper drum. So that, apart from small inaccuracies in the intermediate gearing, the circumferential movement of the paper is proportional to the movement of the poise-weight, and therefore to the load on the specimen.

In this way a diagram is drawn having for its abscissæ the loads on the specimen, as given by the position of the poise-weight, and for its ordinates the extensions taken directly from the specimen itself.

In the case of a test carried out in the usual way the beam is kept floating, and the position of the weight on the beam is a measure of the load on the specimen, and is always taken as such. Even with the most ductile of the metals there is little difficulty in manipulating the beam so as to keep it in equilibrium up to the maximum

Fig. 109.

load. But in the case of ductile metals the actual breaking load is usually less than the maximum. It is between these two points that the local contraction is taking place, and the load-strain curve shows a turning backwards at this point, the load decreasing as the extension goes on rapidly increasing. It is when this period is reached that there is some difficulty in manipulating the poise weight so as to keep the beam floating until fracture takes place. As soon as the local contraction sets in the speed of extension begins to increase rapidly, and it requires a considerable amount of skill and quickness to run the weight back quickly enough to keep the beam floating. If the beam can be kept floating until fracture does take place, the diagram produced by the present apparatus will be correct and satisfactory except for the effect of backlash, but if the operator is unable to prevent the beam from falling on to its lower stop, the diagram will be incomplete. What has been said on this point also applies to other machines which depend for their load indications on the movement of the poise-weight.

In the somewhat similar apparatus of Professor Hele-Shaw, instead of the drum motion being taken from the weight through the screw gearing, the motion is taken direct by means of an endless band connected direct to the poise weight and passing over guide pulleys. Mr. Aspinall's arrangement is very similar.

128. Riehlé's Autographic Apparatus.—On Fig. 109 is shown a general view of one of Messrs. Riehlé Bros. standard machines (capacity 100,000 lb.) fitted with automatic controlling apparatus and autographic gear. The automatic apparatus constitutes the arrangement whereby the position of the poise-weight is controlled automatically. At the outer end of the beam are two electrical contact points, so arranged that when the beam rises to its highest position the points come into contact. The effect of this contact is to complete the circuit of a current provided by means of a battery of two cells. When this circuit is completed, the armature of a magnet is attracted, and this puts the screw controlling the poise-weight in gear with the driving mechanism of the machine, and the weight is carried outwards towards the end of the beam. As the load on the specimen is in this way increased, a further extension takes place, the beam again falls, and the contact is broken. The straining mechanism continues to pull on the lower end

of the specimen the beam is again raised, and the contact effected, and so in this way an automatic balance is maintained. There is a provision whereby the speed of running out the weight can be varied to suit the particular kind of test which is being made.

The drum which carries the autographic diagram will be seen in the illustration. The diagram is drawn by the drum being rotated by the stretch of the specimen, combined with the vertical movement of the pencil due to the load variation. The stretch is taken directly from two clips attached to the specimen, and transmitted to the drum by means of a small shaft and mitre gearing, the linear movement being converted into rotary motion and, between the specimen and the drum, being magnified five times. The vertical movement of the pencil is effected by means of a screw which derives its motion from the poise-weight screw, but on a reduced scale.

This machine can be used with or without the automatic attachment, and the machine can be controlled entirely by hand. When the automatic gear is used it is only necessary to put the straining mechanism in action, and, by means of the apparatus, the load on the specimen is automatically adjusted so that balance is always maintained. The speed at which the poise-weight travels along the weigh-beam can be varied at the will of the operator.

As in the case of Unwin's apparatus, and others of the same type, there is the objection, which has already been pointed out, that the load movement of the pencil is only an accurate measure of the load on the bar so long as the beam is in equilibrium. This is, however, very nearly approximated to by the use of the electrical apparatus. The movement of the weight is, however, only an outward one, and the portion of the diagram near the end of the test when the bar is in its plastic stage cannot be drawn correctly by this apparatus. If it is wished to obtain this portion of the diagram for a ductile material, the electrical apparatus will have to be put out of gear and the machine controlled by hand.

129. Riehlé-Gray Autographic Apparatus.—One peculiarity of this instrument is that, instead of drawing only one diagram, it produces two, one for the complete test up to the breaking load, and the other, a diagram showing the relation between load and strain, up to a point just beyond the elastic limit. On Fig. 110 is shown the instrument in

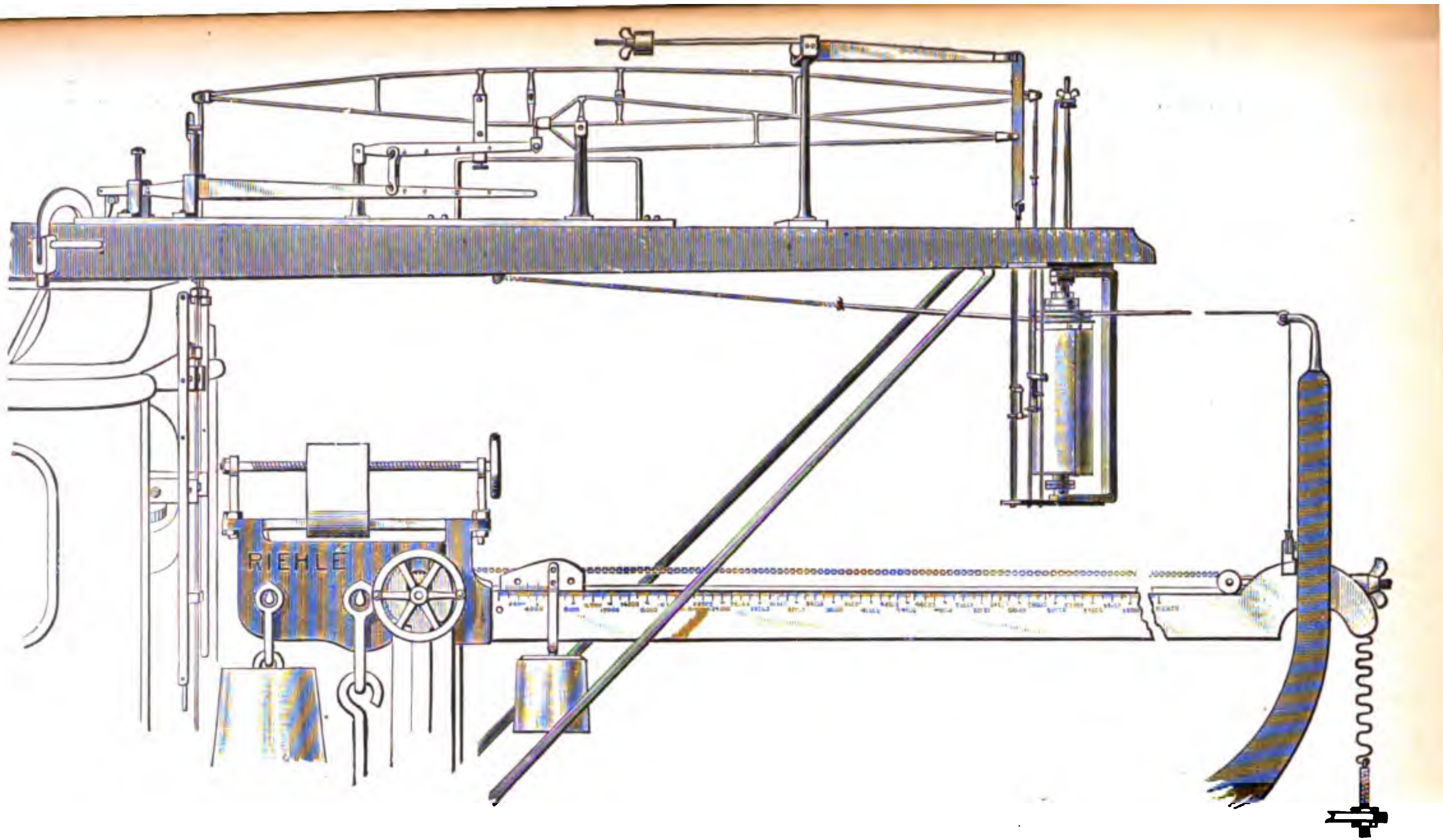
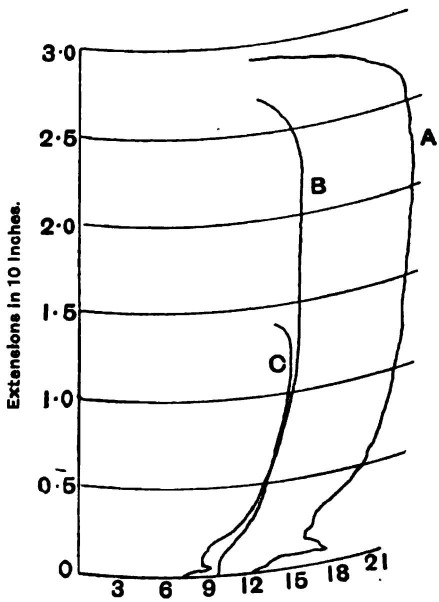


FIG. 110.—RIEHLÉ-GRAY AUTOGRAPHIC APPARATUS.

position, along with the weighing lever of the testing machine. The connection between the test specimen and the recording pencils is made through two sets of levers, as will be seen in the illustration. Two pencils are used, one of which is suspended from the long arm of the large lever having a three-to-one velocity ratio, and thus magnifying the extension three times; while the second pencil

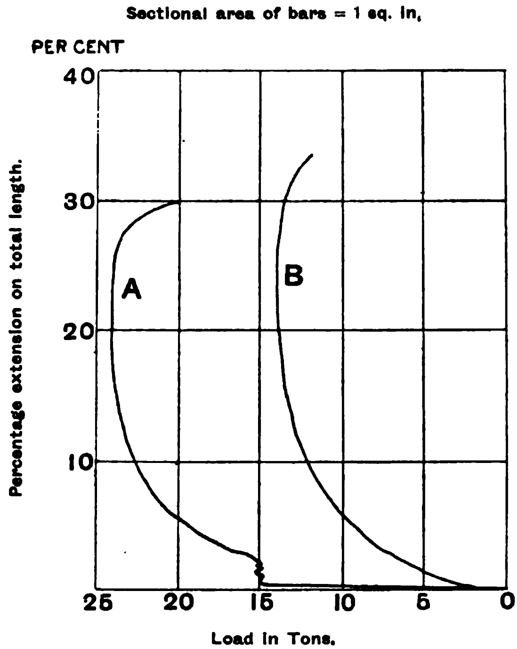


A—Swedish bar iron.
B—Landore rivet steel.
C—Cast steel.

FIG. 111.—Automatic Stress-strain Curves, drawn with the Kennedy-Ashcroft Instrument.

is hung from the third of a set of levers having a total velocity ratio which can be set to 100, 200, 300, 400, or 500 to 1. The former of these pencils is used as in the instrument last described for drawing the diagram covering the whole test. The second pencil, which has a movement from 100 to 500 times the stretch of the specimen, is used within the elastic limit, or to a point

just beyond it. There is an arrangement by means of which high multiplications can be made use of throughout the test. This is effected by bringing the pencil back to zero each time it approaches the edge of the paper. The radical difference between this apparatus and the Riehlé instrument is in the manner of obtaining the load ordinate. The use of the poise weight is dispensed with for the time being, and the load on the specimen is made to lift the weighing lever against the tension of the spiral spring



A—Mild steel.
B—Copper.

FIG. 112.—Copies of Self-recorded Diagrams, taken on a Wicksteed Test-Recorder.*

shown in the illustration. The outer end of the beam has a vertical motion of several inches, its height at any moment depending on the load on the specimen. By means of a cord this movement of the weighing beam is transmitted to the paper drum, which it causes to rotate. The poise weight may be used to check the readings given

* See Inst. Mech. Eng. Proc., 1886.

by the spring. Some of the later machines have been made with a poise which is propelled by a screw and operated either automatically or by hand, thus going back to the less perfect system of taking the load indications from the position of the poise.

130. Other Autographic Appliances.—Besides the devices which have been described, there are many others in use. The principles involved are the same in most cases, the actual

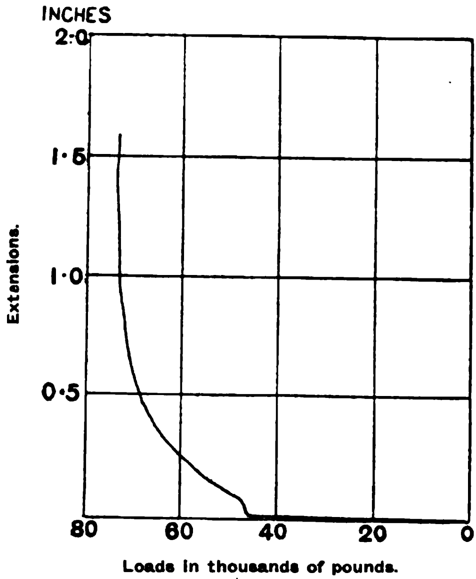
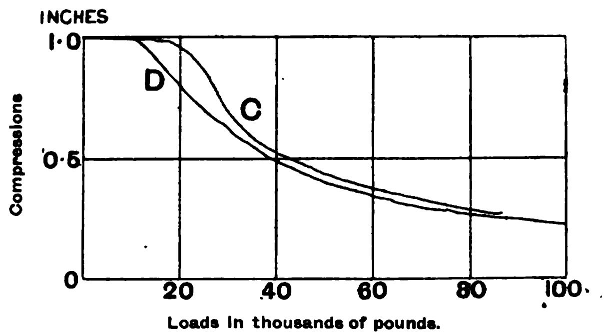


FIG. 113.—**Autographic Diagram, from Specimen of Machinery steel by the Riehlé Apparatus.**

differences being chiefly in matters of detail. The great majority of autographic gears suffer from the defect which has already been pointed out, namely, that the load movement is made to depend on the position of the poise weight, and is not controlled by independent means. The difficulties of attempting to effect this are great, and, moreover, an apparatus which is free from this defect must of necessity be costly.

Autographic gears have been applied to tests other than those in simple tension or compression. In some cases autographic records have been taken of cross-bending tests, as well as those in torsion. Of the latter, two machines

have already been described to which autographic devices are attached. The Buckton torsion machine draws a spiral diagram on a disc, which is rotated by connection with the free end of the specimen, and which is made to revolve through the same angle. The radial movement of the pencil in this apparatus is derived from the movement of the poise weight, which is used to increase the twisting moment on the specimen. The autographic apparatus attached to the Deely torsion machine has already been mentioned. This is really a Crosby steam-engine indicator,



C—Cold rolled steel.
D—Muntz metal. Specimens, 1 in. long and ½ in. diameter.

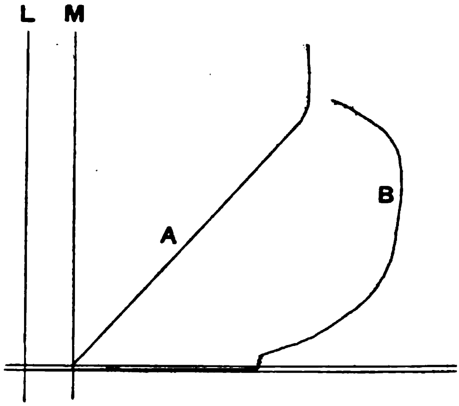
FIG. 114.—Autographic Compression Diagrams, from Riehlé's Apparatus.

the rotatory movement of the drum being derived from the twist of the specimen, and the pencil movement depending upon the motion of the lever against the controlling spring.

131. **Autographic Diagrams.**—The diagrams produced by these various appliances are of course similar in form to diagrams plotted from sets of recorded observations, and should be, putting aside defects and inaccuracies of the apparatus used, precisely the same. Examples of diagrams produced by the appliances just mentioned will be seen on the following figures.

On Fig. 111 are shown three samples of diagrams taken with Professor Kennedy's apparatus. In this case the load abscissæ lie on parallel circles, although the stretch ordinates are in vertical straight lines. In order to compare diagrams of this kind with those having rectangular

co-ordinates, it will be necessary to re-plot them on squared paper. With regard to the diagrams themselves, it will be seen that the elastic portion of the curves in all cases coincides with the base line, the scale being such that the



L—Zero Line, 4 Magnifications.
M—Zero Line, 347 Magnifications.

FIG. 115.—Riehlé-Gray Autographic Diagrams from Tension Specimen of Machinery Steel.

elastic extensions are inappreciable. The elastic limit is well marked, but it will be noticed that the curve beyond the limit follows a somewhat erratic course before settling down to the semi-plastic extension; after the limit load is passed the extensions increase rapidly with the increase of

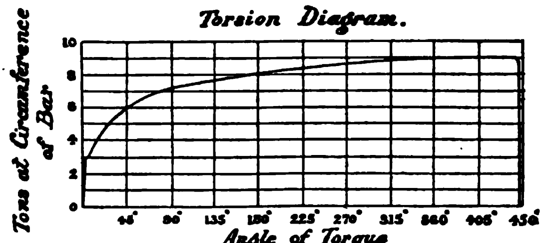


FIG. 116.*

load for some little time, and then, as the extension increases, it will be noticed that the load diminishes again slightly for a time, and then continues to increase,

* Inst. Mech. Eng. Proc., 1898.

showing that when the limit has been passed there is a rapid yielding of the substance with a diminution of load.

On Fig. 112 will be seen two diagrams taken with Mr. Wicksteed's autographic apparatus. That marked A is from a specimen of mild steel, while B is taken from a tension specimen of copper. The general form of these curves is similar to those taken by Professor Kennedy's instrument, and it will be noticed that the turning back of the curve just beyond the limit is again well marked. In this apparatus, as the load ordinate is proportional to the

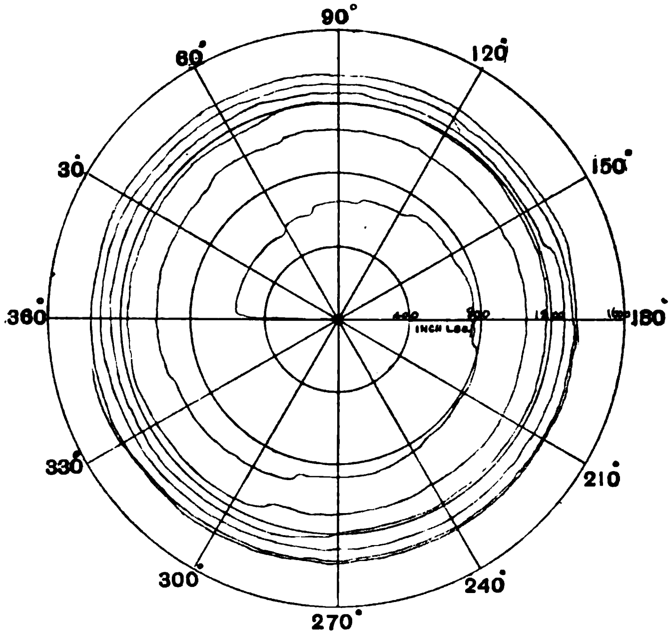


FIG. 117.—Torsion Diagram for Mild Steel Specimen.

actual load on the specimen, and is independent of the movement of the poise, the portion of the diagram representing the last stage of the test during which the local extension takes place is automatically produced.

The diagrams of Figs. 113 and 114 are samples of the curves produced by the Riehlé apparatus. Of these, Fig. 113 is for a mild steel tension test; Fig. 114, C, is from a

compression test of mild steel, and D is from a similar test of Muntz metal. Owing to the fact that the load ordinate depends on the movement of the poise, the tension diagram terminates at the maximum load.

A diagram produced by the Riehlé-Gray apparatus is represented in Fig. 115. Here two curves are shown, that marked A being the elastic curve, in which the stretch is magnified 347 times, and B the curve for the whole test, in which the stretch is magnified four times. In this latter

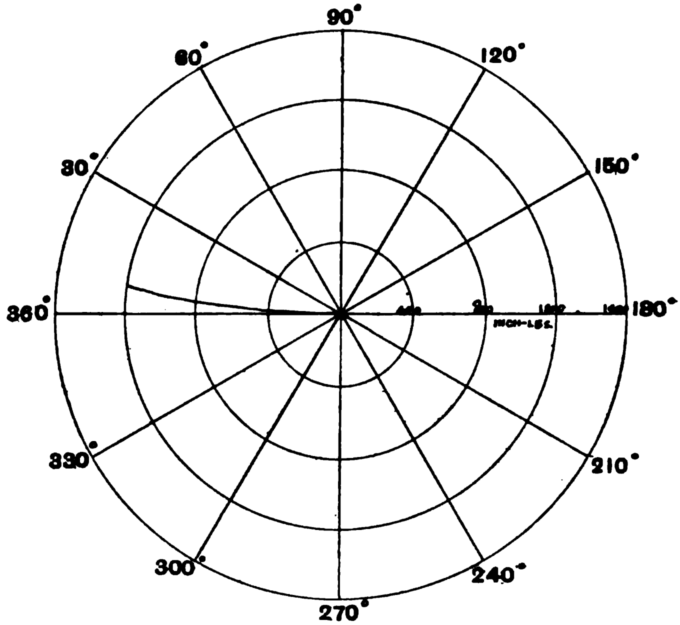


FIG. 118.—Torsion Diagram for Cast-iron Specimen.

case the diagram gives true indications up to the actual point of rupture. The material tested was a specimen of machinery steel.

On Fig. 116 is an autographic diagram taken on a Deeley torsion machine. The material tested was a piece of crank axle steel.

Two spiral torsion diagrams taken by the writer on a Buckton torsion machine are shown in Figs. 117 and 118, the former being for a specimen of mild steel 5 in. long and 0·473 in. diameter, and the latter is for a bar of cast iron

having the same dimensions. In these torsion diagrams for ductile metals the elastic limit is very well defined.

Similar diagrams to these, but taken from much larger specimens, by Mr. Charnock, at the Bradford Technical College, were published in *Engineering* some years ago.

It was pointed out that, by means of the Riehlé-Gray automatic apparatus, it is possible to draw a curve showing the relation between stress and strain within the elastic limit, in addition to the one for the complete test, the extensions being magnified several hundred times. Dr. Kennedy has produced diagrams similar to these by making use of the apparatus already described (Fig. 106, p. 222 *ante*), in a somewhat modified way. When a diagram of this kind is to be drawn with the apparatus, the spring-piece is dispensed with, and the instrument fixed upon the specimen itself, by which it is supported. In this case the swinging pointer does not record the load, but the magnified stretch of the specimen. The indications of load variation are obtained direct from the poise weight, whose movement is transmitted to the sliding glass plate upon which the diagram is to be drawn. There is not here the same objection to taking the load from the poise as in the former cases, because the loads and strains are both progressive and there is no going back of the stress; there is no difficulty in keeping the weighing beam floating throughout the drawing of the diagram. An example of a figure produced with this device is shown on* Fig. 119. The test was made upon a sample of cast iron ¾ in. diameter and 10 in. long. Three curves are shown, taken one after the other from the same bar. The zero line for extensions is A B. The first diagram taken is marked L. When a certain point was reached the load was removed, and the needle went back, not to the point A, but to a higher point C, the distance A C representing the permanent set after the first loading. The process was now repeated, the curve starting from D and almost coinciding with the first curve at the end. A smaller amount of permanent set is shown in this case. A third diagram was drawn, this being almost identical with the second.

It must be remembered that the extension ordinates produced with this apparatus are on circular arcs, and the whole curve must be replotted when it is desired to

* Taken from Professor Kennedy's paper in Min. Proc. Inst. Civil Engineers, vol. lxxxviii.

compare it with similar curves having rectangular co-ordinates. The magnification of the extensions used in this case was 130 to 1.

132. Uses and Limitations of Autographic Diagrams.— Autographic stress-strain diagrams are sometimes described as being analagous to indicator diagrams taken from fluid-pressure engines, but this is an unfair comparison. The two cases are not quite similar. An indicator diagram is taken from an engine for two purposes, one qualitative and the

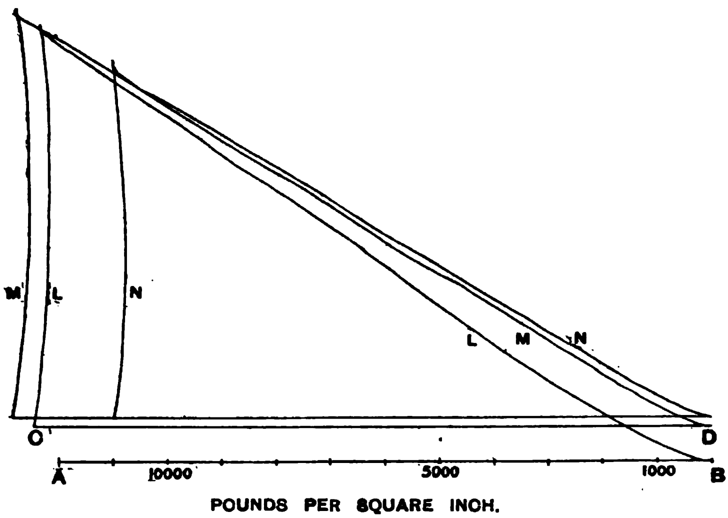


FIG. 119.—Automatically drawn elastic load strain diagram of a sample of Blaenavon Cast Iron. L is the curve for the first loading, M for the second, and N for the third.

other quantitative. It is required to determine the work which is being performed upon the piston of the engine during a cycle or number of cycles; and, at the same time, the diagram is made use of for the purpose of finding out the manner in which the parts of the engine are doing their work. No other means are available for determining these two sets of facts—the time taken to complete the cycle of an engine is relatively short; and, therefore, it is for this reason not possible to take a number of isolated readings, and to plot the complete diagram afterwards from these. The indicator must be relied upon almost entirely, and there is no appeal against its decision.

But with an autographic apparatus applied to a testing machine the case is different. It is here possible to take observations at different parts of the test, and from these recorded results to plot a complete load-strain curve. With the exception of the interval between the elastic limit and the semiplastic curve, and that part of the curve beyond the maximum load, a curve plotted from isolated observations may be regarded as somewhat more accurate than the curve for the same test produced automatically, owing to the imperfections of the instruments used. And, at the same time, it is much more accurate to rely on direct observations of the poise weight for such quantities as the maximum load, and any other isolated readings that may be required. The autographic apparatus, therefore, must be regarded as subservient to the direct observations which must always be taken, and not in any way as replacing these. The result of an ordinary commercial test must be made to depend on direct observations taken by the person conducting the test, and recorded by him, although a diagram may be drawn automatically while the test is proceeding, but this shall in no way interfere with the test as ordinarily carried out.

What, then, are the uses of an autographic diagram at all? It must always be remembered that an automatically produced diagram is of necessity of secondary importance to a set of direct measurements. But, at the same time, it has its uses, both qualitative and quantitative. In the first place, autographic diagrams are useful when a number of tests of similar material are made. A comparison of the curves produced by these different specimens shows at once variations as to the elastic limit, maximum load, and the ductility of the bars, both general and local. Again, the relations as to stress and strain at that point of the curve just beyond the elastic limit, can only be satisfactorily obtained by means of a diagram drawn by the specimen itself, so long as the appliance used to produce the curve is not made to depend in any way upon the position of the poise weight. The same may be said of the portion of the curve which turns backwards beyond the maximum load, if the material is ductile.

For quantitative purposes the automatic diagram has only a very limited use. Actual measurements of definite quantities, such as the maximum load and the total extension (in the case of a tension specimen) should never be taken from the autographic diagram, but should be

made to depend upon direct measurements, though in certain cases they may be used as a rough check on the latter. The area of a stress strain diagram is a measure of the mechanical work performed upon the specimen in breaking it, and it is a not unusual way of expressing the quality of a material to calculate the work done on the bar up to the point of rupture per cubic inch of its volume. A convenient method of ascertaining the amount of this work is by measuring the area of the load-strain diagram by means of a planimeter. The same result may, of course, be arrived at by taking a number of isolated observations and plotting the diagram, but this is too slow and laborious in the case of most commercial tests. There is also an approximate method of arriving at the same results, depending upon the maximum load and the final extension.

For the purposes of scientific investigation a reliable autographic apparatus, such as the one used by Dr. Kennedy, may be made extremely useful. It is possible in such a case to observe minute changes of stress and strain, which are difficult, and, in many cases, impossible, to obtain in any other way. This applies especially to the portion of the stress-strain curve at or near the yield point, and also that part beyond the maximum load up to the point of fracture.

It should be pointed out that the dimensions of a diagram are affected by the magnitude of the time interval allowed to elapse during which the test is carried to a completion. Deformation during the semi-plastic and plastic stages does not take place instantaneously, but the material must be allowed time to take up its set. Consequently, a test rapidly carried out will show less permanent strain than one more slowly performed, and it does not follow that because two specimens are exactly similar in every respect that that they will produce precisely similar autographic stress-strain diagrams, although the general characteristics may be the same.

The use of autographic diagrams for quantitative purposes in commercial testing has been deprecated, and in this connection it has often been pointed out that diagrams of this kind can be tampered with. This is, of course, true, but it is not much more likely that a man who is carrying out a test will tamper with the diagram his machine is producing than that he will intentionally misinterpret direct observations, or that an observer in a

steam-engine trial is likely to interfere with the proper action of the indicator. The principal reason why autographic gears ought not to be used in the place of direct readings is that the accuracy of the latter is of necessity greater and their results more certain.

133. Work done in Fracturing a Test Bar.—A very good criterion as to the useful properties of a ductile material is the amount of mechanical work that must be expended on the bar by the testing machine in straining it up to the point of fracture against the gradually increasing load. This quantity is generally expressed as so many inch-tons

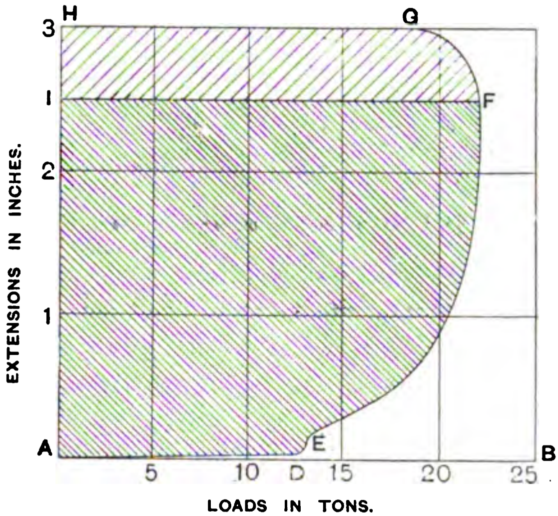


Fig. 120.—Diagram showing the Work done in fracturing a Test Bar.

per each cubic inch of the original volume of the metal. The term "original volume" is used here because, although for all practical purposes the volume remains constant during the test, a small variation does in reality occur. The work so done may be ascertained in various ways. In the first place, a diagram may be plotted from a set of direct observations taken at frequent intervals during the test, and the area of this curve measured; or the same thing may be done with an autographic diagram; or the work may be calculated by means of an approximate formula suggested by Dr. Kennedy.

On Fig. 120 will be seen a reproduction of the load strain diagram already given, and plotted from the results

of the tests of a mild steel bar (see Fig. 68, p. 148). This may be taken as a typical load-strain curve. It may also be supposed to be either plotted from individual results, or to have been produced by means of an automatic apparatus.

The whole life of the test bar, from the time when the load upon it is first applied, may be divided into four stages. Referring to the diagram, from A to D the bar is elastic, and its strains are relatively small, and not permanent; this is the elastic stage. At D the limit is approached, and the strains are greatly increased. From D to E is the second stage, during which the bar is in a state of unstable equilibrium, the stress alternately increasing and decreasing with the strain, and producing an uneven and serrated curve, if the diagram is automatically drawn; this may be due to a succession of sudden local yieldings of the material. When the point E is reached, the uniform semi-plastic stage begins; here the strains and stresses increase together in a uniformly varying ratio. At F the maximum load is reached, and the third stage is complete. From F to G represents the fourth and last stage, during which the strain is chiefly that due to local extension. The fourth stage is complete at G, which marks the point of fracture of the bar.

Mechanical work is the product of a force into the linear distance through which it is exerted. The force or load on a test bar is represented on the diagram by horizontal measurements parallel to the base line A B, and from the zero line A H. Strains are measured vertically upwards from the zero line A B. The total strain is the distance through which the varying load has done its work. The area A H G F E D of the diagram is the product of horizontal and vertical linear measurements. Therefore the area represents, to some scale, the total work done upon the bar in breaking it.

Thus, if m is the number of tons represented by one inch, horizontally, n is the number of inches of strain represented by one inch vertically, and a is the measured area of the diagram in square inches.

Then $m.\,n.\,a.$ will be the work done on the bar in inch-tons.

The area of the diagram may be ascertained by means of a planimeter. In the present instance the area, a, is found to be 17·48 square inches.

$$m = 5, \text{ and}$$

$$n = \frac{2}{3},$$

so that the work done on the bar is—

$$
\begin{aligned}
W &= m.\ n.\ a. \\
&= 5 \times \frac{2}{3} \times 17{\cdot}48, \\
&= 58{\cdot}30 \text{ inch-tons};
\end{aligned}
$$

and the work done per cubic inch of the original volume of the bar is—

$$
\begin{aligned}
w &= \frac{W}{l\,A} \\
&= \frac{58{\cdot}30}{10 \times 0{\cdot}788} \\
&= 7{\cdot}39 \text{ inch-tons},
\end{aligned}
$$

where l is the original length of the bar, and A is the area of the original cross section.

The same result may be obtained by making use of the approximate formula suggested by Dr. Kennedy,* and based on the assumption that the semi-plastic curve is a parabolic one. In this formula—

P is the maximum load in tons,
e is the total extension in inches,
and r is the ratio of limit to maximum.

The formula gives the total work done on the bar as—

$$W = P\,e\left(\frac{r + 2}{3}\right)$$

and the work done per cubic inch is—

$$w = \frac{P\,e}{l\,A}\left(\frac{r + 2}{3}\right)$$

In the present instance the values of the symbols already given are—

$$
\begin{aligned}
P &= 21{\cdot}90 \text{ tons}, \\
e &= 3{\cdot}06 \text{ inches}, \\
l &= 10 \text{ inches}, \\
A &= 0{\cdot}788 \text{ square inches}, \\
r &= \frac{13}{21{\cdot}9} = 0{\cdot}594.
\end{aligned}
$$

From which the result is obtained that—

$$
\begin{aligned}
w &= \frac{21{\cdot}9 \times 3{\cdot}06}{10 \times 0{\cdot}788}\left(\frac{0{\cdot}594 + 2}{3}\right) \\
&= 7{\cdot}34 \text{ inch-tons per cubic inch.}
\end{aligned}
$$

* See Inst. Mech. Eng. Proc., 1886, p. 68.

This is very near the result obtained from the diagram, which was 7·39 inch-tons.

Both this, and the result obtained from the diagram above, give the total work done upon the bar up to the point of fracture as represented by the area A H G F E D. The objection to the use of this method is that it includes the work done beyond the maximum load at F, and, in consequence, is not independent of the proportions of the bar. It would, therefore, seem to be better, and to make it possible to use these figures for comparing bars of various dimensions and ratios of length to diameter, not to include the work I H G F, but simply to measure the area A I F E D. The above formula does not apply to this case, as it depends upon the extension after fracture, and not on the extension at the maximum load.

In order to find the work done per cubic inch without taking account of the local extension, when this exists, some means must be adopted by which the local extension may be eliminated.

The extension on the several inches of length were as follow:—

EXTENSIONS ON EACH INCH.

1st	0·19 inch.
2nd	0·20 ,,
3rd	0·21 ,,
4th	0·24 ,,
5th	0·28 ,,
6th	0·29 ,,
7th	0·30 ,,
8th	0·60 ,,
9th	0·50 ,,
10th	0·25 ,,
Total, neglecting 8 and 9	= 1·98

This total of 1·98 inches is on the 8 inches which do not partake of the local contraction.

Using Kennedy's formula again, we have:

$$w = \frac{P\ e}{l\ A} \left(\frac{r + 2}{3}\right)$$

$$= \frac{21·9 \times 1·98}{8 \times 0·788} \left(\frac{0·594 + 2}{3}\right)$$

$$= 5·96 \text{ inch-tons per cubic inch, } \textit{neglecting}$$

local extension.

This has been done, it will be at once apparent, by taking away the inches 8 and 9 to which the local extension is confined and reckoning the work on the remaining eight. Measuring the area of the diagram A I F E D with the planimeter, it is found to contain 14·14 square inches. Dealing with this as before, it is found that the work performed per cubic inch is

$$= \frac{14{\cdot}14}{10 \times 0{\cdot}788} \times \frac{2}{3} \times 5$$

$$= 5{\cdot}98 \text{ inch-tons.}$$

This agrees very well with the result obtained by the approximate formula.

CHAPTER VIII.

TESTING OPERATIONS—(*Continued*).

TESTS OF ROPES, WIRE TESTS, TESTS UNDER VARIOUS TEMPERATURES, HARDNESS TESTS, AND TESTS OF CHAINS.

134. Tension Tests of Wire Ropes.—The arrangement of the wires in a rope varies greatly, according to the use to which the rope is to be put. Generally speaking, a number of wires are twisted together so as to form a strand, and a number of these strands are again laid together so as to make up the whole rope. The simplest arrangement of the wires is to have six placed symmetrically around a central wire of the same size. This is shown on Fig. 121. In some strands a second ring of wires is arranged on

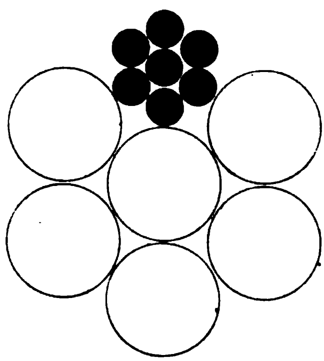


FIG. 121.—Section of 49-Wire Rope.

the outside of the existing seven. The central wire, or core, of a strand is sometimes composed of similar metal to that of the other wires. More frequently this central wire is of very soft metal, while the others are harder. When this is the case, the central wire is not regarded as adding anything to the strength of the rope, but simply acting as a core upon which to build the strand. The reason for doing this is that on account of its position this

central wire would, in the ordinary course of things, have to bear a greater load than the others, and would snap if of as hard metal, but being of soft annealed metal it can stretch freely without breaking, and so damaging the rope as a whole.

The arrangement of the rope is most frequently in six strands wound round a central core. This core may be either a similar strand or a piece of tarred hemp strand. This latter arrangement, while decreasing the strength of the rope by one strand, adds very much to its flexibility. Ropes built up of a large number of wires of small diameter, and having a fibrous core, are much more flexible than those made of large wires with wire cores.

If all the wires in a rope could be subjected to exactly the same tension, providing they were all of the same material, the strength of the rope would be equal to the combined strength of all the individual wires forming the rope. Generally the load which is required to fracture the rope is some ten or fifteen per cent less than the total strength of the wires. This is owing partly to inequalities in the metal forming the various wires, but chiefly to the varying tightness of the wires and the consequent unequal load upon them.

The chief difficulty in carrying out a complete test of a wire rope, or indeed a rope of any kind, lies in finding a satisfactory method of holding the ends. Various means have been tried with more or less success. The usual forms of holders, such as are used for attaching the ends of colliery winding ropes, are generally less strong than the rope itself. Of the many tests made in the direction of finding the most suitable holder, those of Mr. W. Hewitt, of Trenton, N.J.,* are especially interesting and valuable. In the tests carried out by him several forms of fastenings were tried with varying results. Fairly good results were obtained with ordinary thimbles spliced in place. Of these, some were broken in the body of the rope, while in several the failure took place in or near the splice. A number of tests were tried with the ends of the ropes fastened in sockets after the manner usual in winding ropes. These were all pulled out of the sockets and the tests were rendered useless so far as the ropes themselves were concerned. In this method of holding, the ends of the rope are first frayed out, and the ends of

* Proceedings of the American Institution of Mechanical Engineers, 1888, page 671.

the individual wires turned inwards over an annular wedge; the whole is placed in a conical socket and the interior of the ring filled in with points, or a conical wedge is driven in. Strong as these holders or cappings appear at first sight, when placed in a testing machine, it is nearly always found that the wires are pulled out of the socket with little damage to the rope itself. The fact that spliced thimbles hold much better than sockets shows that mutual friction between the wires of the rope is of more avail than the friction between the wires and the surfaces of the sockets. Another form of fastening used in these tests is a socket

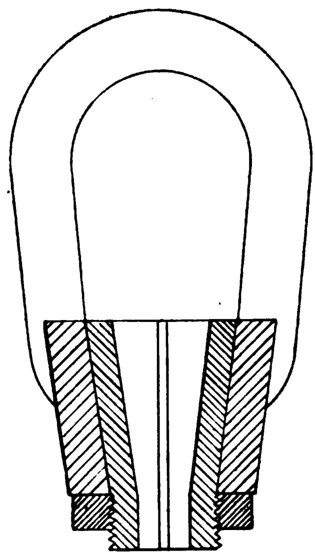


FIG. 122.—Socket used by Mr. Hewitt.

of the form indicated in Fig. 122. The socket is bored out to the required taper, and is fitted with a shell, or bush, made in three pieces, and having a screw thread at its outer end. The wires at the end of the rope are frayed out and bent back against the body of the rope. Some of the wires are left longer than the others, so that a conical bunch or head is formed. This is surrounded by the shell, which is itself placed in the socket. A nut is screwed on to the shell and the wires drawn tight, and in this way firmly clamped. In some cases molten white metal is poured into the socket, so as to fill up the interstices.

The combination of mechanical friction with the direct pull against the white metal makes a sound job, but an equally satisfactory attachment can be made with the white metal alone. This may be done by fraying out the ends of the rope, having previously bound the rope with wire to prevent the wires from becoming loose. The ends of the wires are bent over for about 1 in. of their length, the whole forming a conical bunch. This can then be placed in the socket, which should have a small taper, and be as long as possible. Before being placed in the socket the wires should have been cleaned in acid and the inner hemp core (if any) cut out. The whole may then be poured full of some fairly hard white metal. This holder (Fig. 123), as used by Professor Goodman, of the Yorkshire College, rarely fails to hold the rope securely, and the rope most frequently breaks in the body somewhere between the two holders. A great desideratum in wire rope testing is that there shall be a uniform tension on all the wires which go to make up the rope. This end is probably more certainly attained with a fastening in which the wires are surrounded by a solid mass of metal than where friction is depended upon.

In this connection Johnson* recommends that after the ends of the rope have been boiled in caustic soda, and thoroughly washed in hot water, they should be dipped in chloride of zinc and then in molten solder, so that the wires are tinned. The alloy recommended is one consisting of tin, lead, and antimony. Tejmager makes use of an alloy of eight parts tin, one part copper, and one part antimony for iron and mild steel wires; and nine parts lead, two parts antimony, and one part bismuth for hard steel wires. Pierre Arnould† used for his alloy equal parts of lead and zinc.

Rouleaux‡ recommends, among other means for holding the ends of a wire rope, a socket in which the rope is unravelled, the wires turned inwards, and molten metal poured in. This socket is indicated on Fig. 124. From what the writer has seen of the tests of various holding devices, he is led to believe that of the holding sockets based on the wedge principle very few indeed are as strong

* "Materials of Construction," page 691; also see *Engineering*, September 11th, 1896.

† Proceedings of the Institution of Civil Engineers, vol. xcviii., p. 412.

‡ "Constructor," p. 182.

as the rope itself. In nearly all cases when subjected to loads in a testing machine the ropes are pulled out of the sockets without breaking.

When the rope which is to be tested has had its ends prepared in the manner described, the test may at once be carried out. In order to prevent any give or settling in the socket when the load comes to be applied, it is well,

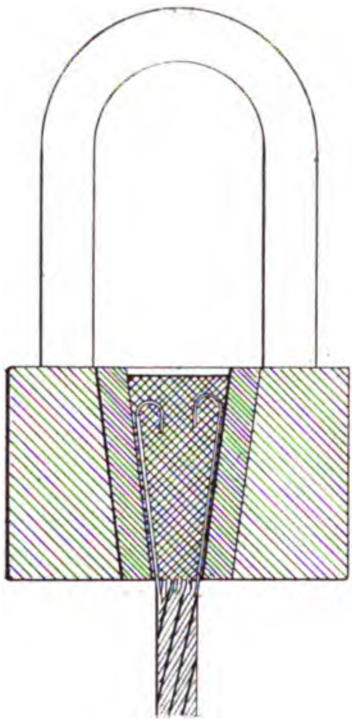


FIG. 123.—Fastening in which White Metal Matrix is used.

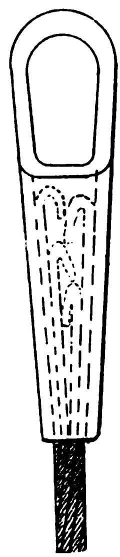


FIG. 124.—Rouleaux' Socket.

if possible, to cast the white metal matrices in the actual sockets which are to be used in the testing machine. Any wrapping which has been put upon the rope during its preparation must be removed. During the progress of the test measurements of any extension that takes place in the rope make be taken. The most important point to observe is the load at which the specimen actually fails. This failure, in a satisfactory test, takes place by a rupture

of several of the wires at a point which is between the two holding sockets; sometimes one or two of the strands fail; it is not often that the rope as whole breaks at once. If the ends are not held in a satisfactory manner, the rope may be pulled out of one of the sockets, or the fracture of a number of the wires may take place inside the socket through unequal tension.

When a length of rope is tested it is usual to test also a number of the wires which go to make up the rope, and to compare the combined strength of these with the strength of the rope itself. Wires must not be taken at random from the rope, but if all the individual wires forming the rope are not tested all those making up one strand are to be tested, and the combined strength of these, multiplied by the number of strands, gives the nominal strength of the rope. By doing this the one soft wire in each strand is tested along with the others of the strand, and not several, as might be the case if the wires were selected at random.

The testing of these individual wires may be most conveniently performed in a special wire testing machine or a smaller type of general testing machine. Many machines are made to suit the special requirements of wire manufacturers. For wire testing, wedges are used, for holding, with the gripping surfaces finely cut. When the wires of a rope are being tested there is no need to take any other measurements than the breaking loads.

The following is an example of a complete test given by Mr. Biggart in his paper on wire ropes. This rope was one made by Messrs. Bullivant, and consisted of crucible steel wires.

TENSILE TEST OF A STEEL WIRE ROPE.*

Circumference.	Weight per fathom.	Number of strands.	Number of wires in one strand.	Total number of wires.	Diameter of wire.	Area of cross-section of wire.	Breaking load of wire (mean).	Breaking load of wires per square inch.	Total breaking load of wires.	Breaking load of rope.	Efficiency, per cent.
In.	lbs.				In.	sq. in.	lbs.	tons	tons	tons	
$1\frac{3}{4}$	2·00	6	12	72	0·04	0·0013	200	68·68	6·43	5·85	91

This is a fairly good sample of a test of such a wire rope. There are six strands in the rope, so it is to be

* Minutes of proceedings of the Institution of Civil Engineers, vol. ci.

assumed that there was a hemp core or centre, around which the strands were laid. Instead of testing all the wires of one strand, and assuming all the strands to be of the same strength, the less reliable plan was here adopted of testing six wires from any part of the rope, and taking the average of these as the nominal strength of one wire.

The average diameter of the wires is given as 0·04 in., which is equivalent to a sectional area of 0·0013 in. The average breaking load of one wire is 200 lb., so that the breaking stress of the wire per square inch of sectional area is

$$f_t = \frac{200}{0\cdot0013 \times 2240}$$

$$= 68\cdot68 \text{ tons per square inch.}$$

There are 72 wires whose average strength is 200 lb. So that the total nominal strength of the whole rope will be

$$W_N = \frac{72 \times 200}{2240}$$

$$= 6\cdot43 \text{ tons.}$$

When placed in the testing machine, the rope itself fractured at a load of 5·85 tons. If this load be called W_A, then the "efficiency," or the percentage which the strength of the whole rope is of the sum of the strengths of the individual wires, is

$$\epsilon = \frac{W_A}{W_N} 100$$

$$= \frac{5\cdot85}{6\cdot43} 100$$

$$= 91 \text{ per cent.}$$

The reasons why the strength of the whole rope is less than the sum of the strengths of its component parts are several. In the first place, in its original state the wires composing the rope are not all in the same state of tightness, and therefore, when the load comes upon the rope, all do not have to withstand the same tension. This fault may be aggravated by the way in which the rope is held, and it is extremely important that the wires may be so held that there is as much uniformity in the tension on the different wires as possible. This is probably why embedding the individual wires in a matrix of metal is better than relying on wedges alone. Possibly slight damage

may be done to the wires in some cases by the heating during the process of pouring in the molten metal. Where this is used the metal itself should be of such a nature as to allow of no yielding of the wires, and for this reason it should be comparatively hard on setting. If lead is used a small admixture of antimony hardens it and a little bismuth causes it to expand on setting. It is sometimes asserted that the rope itself ought to yield a result better than the total strength of the wires because the wires as they lie in the ropes are inclined to the axis, and therefore present an area to the axial pull greater than the area on a section at right angles to the axis of the wire. The rope, however, must not be regarded as a rigid bar of the metal, and though the wires are to some extent supported in position, the pull is necessarily axial to the wires and not to the rope. If the wires were not supported laterally the opposite effect would be produced of the tension in the wires being greater than the axial tension on the rope. The conditions would appear to be analagous to the case of a wire passing over a pulley, when the tension is sensibly constant at all points of the wire.

135. The Testing of Wire.—The difference between a wire and a larger bar of the same material is not in size alone, but in the condition of the metal forming the wire, a condition caused by the process of manufacture. The effect of wire-drawing, as opposed to rolling, is to produce a condition of greater hardness than the original metal from which the wire has been produced, and also greater tensile strength. This artificially produced hardness may be made to disappear by annealing after wire-drawing, but the tensile strength may or may not be reduced to the strength of the original metal; in some cases annealing lowers the strength below that of the original metal.

The tests to which wire is usually subjected, in order to obtain definite information as to its strength properties are three in number, and are as follow :—

(*a*) Repeated bendings through a definite angle.
(*b*) Torsion or twisting tests.
(*c*) Ordinary tensile tests.

136. Bending Test.—The bending test for wire may be carried out in a special piece of apparatus made for the purpose, or in an ordinary vice. The jaws of the holding vice should be rounded, and made either to

some pre-arranged radius or to a radius equal to the diameter of the wire which is being tested. The test consists in holding the wire in the vice and then bending the portion outside the vice backwards and forwards through a constant angle until fracture takes place, the number of bendings before fracture, the radius of curvature of the jaws, and the angle through which the bending has taken place being noted. To give the reader an idea of what occurs, it may be stated that a piece of iron wire about one-tenth of an inch in diameter, when bent at right angles backwards and forwards over jaws having radii of 0·4 in., fractures after about twenty bendings.

FIG. 125.

137. **Torsion Tests for Wire.**—The torsion test consists in holding a certain definite length of the wire in such a way that one end is firmly fixed and the other end is twisted with respect to it until fracture takes place. Special machines are used for this purpose. A typical example is shown on Fig 125. This machine is made by Messrs. Denison, of Leeds. The grippers for holding the ends of the wire are automatically self-tightening. The end of the wire on the left is prevented from rotating while the right-hand end is twisted by means of the hand-wheel until fracture has taken place, a counter being provided for the purpose of ascertaining the total number of revolutions through which the wire has been twisted. The piece of wire is of a certain definite length, and it is often specified by buyers of wire that it must be able to withstand a certain number of twists on a certain length before fracture takes place. For instance, a piece of good crucible steel wire, 8 in. in length, and No. 20 B.W.G., requires over 100 revolutions

to produce fracture. The initial tension on the wire should be noted if possible.

138. Tensile Tests of Wire.—This test consists in breaking the wire under a tensile load, with or without a measurement of the ultimate elongation. There are a great variety of machines on the market for the purpose of testing wires in tension. A simple form of the machine, previously illustrated (Fig. 37), made by Messrs. Bailey, is largely used on account of its ease of access and convenience

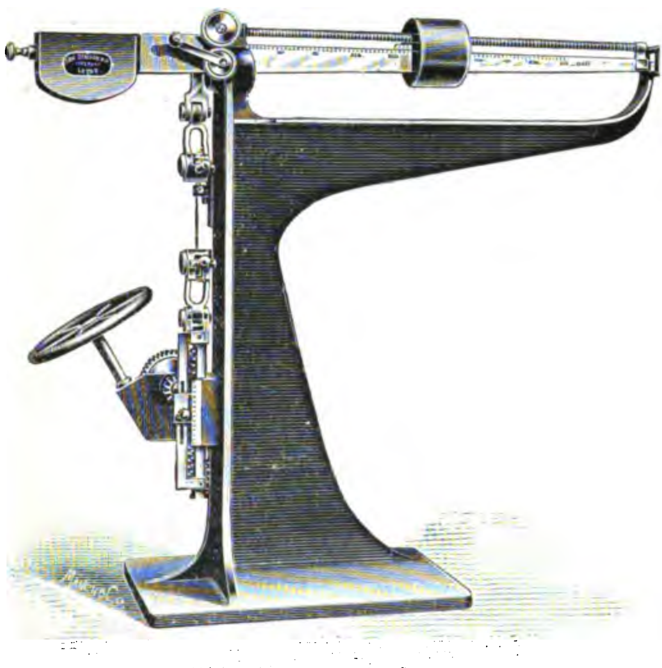


FIG. 126.

in handling. A useful single lever vertical machine, made by Messrs. Denison, of Leeds, is shown on Fig. 126. The holding wedges are finely cut, and are provided with the makers' patent arrangement by which they are under control, and are both advanced, or both receded together. This arrangement enables the wire to be taken hold of very easily and quickly. The stretch of the wire is taken up by a worm-wheel and rack gear, which is

provided with a quick return motion in order to save time. The ultimate elongation of a definite length of the wire may be most accurately found by making two marks on the wire at the required distance before the test, and measuring the elongation on the two broken halves when placed together after fracture. Sometimes this is measured

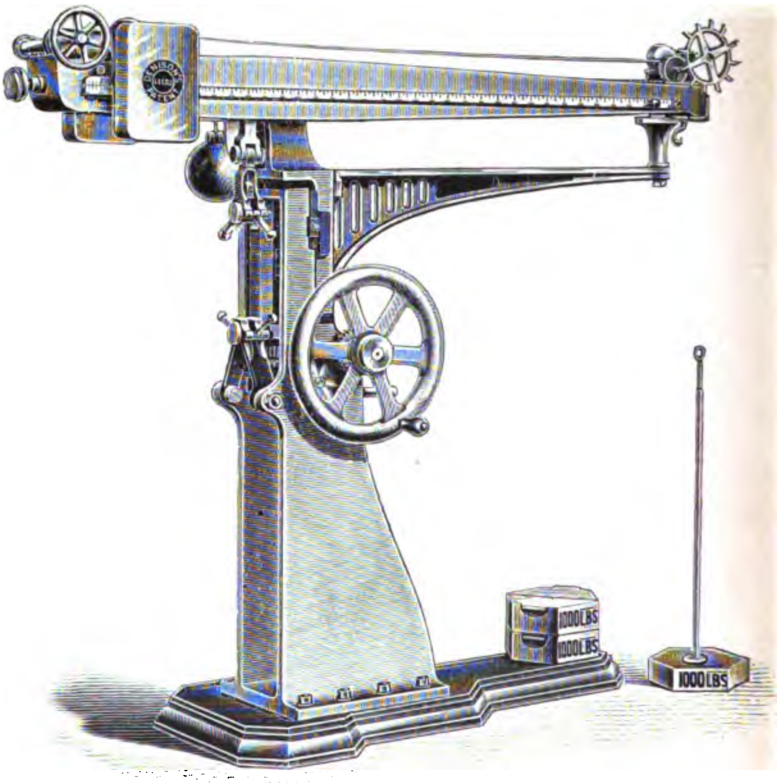


FIG. 127.

during the progress of the test by a measuring apparatus supplied with the machine. This particular machine has a maximum capacity of 1,000 lb. A somewhat similar machine by the same maker's is shown on Fig. 127. This machine is made with capacities of 6,000 lb. and 8,000 lb., The straining is effected by means of a worm-wheel and screw gear arranged in two speeds, one being 15 times as

fast as the other. This fast gear is used for light wire testing. An automatic arrangement is provided, by means of which the poise-weight is carried outwards along the beam by the falling of a weight. This automatic motion only comes into action when the beam is raised above its normal position by the pull on the specimen. This releases the escapement wheel, which will be seen at the end of the beam, and the weight is allowed to move the poise-weight outwards, and so increase the stress, and with it the strain.

139. The Testing of Fibrous Ropes.—Like wire ropes, ropes made of Russian, Italian, Manilla hemp, or cotton are all somewhat difficult to handle in a testing machine, on account of the fact that there are few really satisfactory ways of holding the specimens. The length tested may vary from 18 in. to several feet and is practically limited by the capacity of the testing machine. Of arrangements for holding the ends it is found that both knots and splices are practically useless, as when either of these is used the fracture of the rope nearly always takes place at or close to the knot or splice, as the case may be, and not in the body of the rope, which is what is desired. The failures of this kind of holding seem to be due to the sharp curvature of the rope itself, fracture taking place in a manner analogous to the failure of a beam.

Unwin recommends the attachment used by Kortum for the purpose of holding the ends of a piece of fibrous rope in a testing machine. This is shown on Fig. 128. The holder consists of an outer shell terminating at its upper end in a loop by which attachment is made to the shackle of the machine. The body of this shell is made taper, with the smaller diameter at the outer end. Fitting this taper portion are two gripping wedges, shaped to fit the socket, so that as they are drawn outwards they close inwards. These wedges are also made to taper in the opposite direction on their inside surfaces, which are provided with a number of sharp teeth, so as to penetrate the rope as the wedges are drawn together. When the rope has to be gripped for testing it is only necessary to insert it in the holder and then draw it tight. By this action the wedges are drawn downwards and close in upon the rope, the gripping being tighter at the outer free end than further down, so that the grip on the rope increases from the top downwards. According to Professor Unwin,

this form of fastening has been used satisfactorily for both fibrous and wire ropes.*

An effective method of holding is obtained by the use of a conical socket similar to the one used for wire ropes. One of these is shown on Fig. 129. The end of the rope must be provided with an enlarged end, either by forming a "turk's head" upon it, or by unravelling the portion near the end and knotting the various yarns together. This is shown at A. The space between this enlargement and the body of the rope may be filled in by a wrapping of rope yarn, as at B. If this form of holder is carefully made it will be found that failure will take place in the body of the rope.

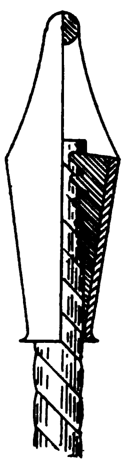


FIG. 128.—Kortum's Rope Shackle.

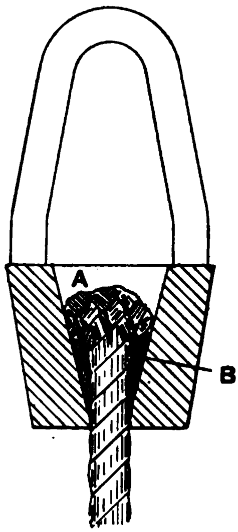


FIG. 129.—Rope Socket.

It has been found that if a number of specimens of varying length are taken from the same piece of rope, and tested, that the shorter ones yield the higher results; this point should be borne in mind when selecting lengths for test pieces. The length of the fibre, which is from $2\frac{1}{2}$ ft. to $3\frac{1}{2}$ ft. in length in a hemp rope, has probably some influence on the difference of strength on long and short pieces.

* Unwin, "Testing," p. 184.

The following is an example of a test of a hemp rope :—

TEST OF AN ITALIAN HEMP ROPE.

Circumference. Inches.	Sectional Area. Square Inches.	Breaking Load. Tons.	Breaking Stress. Tons per Square Inch.
4·5	1·62	7·23	4·47

Of course it must be remembered that this sectional area is only nominal, and does not refer to a solid section but to the area of the circle representing the outer circumference of the rope.

TESTING OF METALS AT ABNORMAL TEMPERATURES.

140. It is important in some cases to test samples of metals at temperatures either above or below the normal temperature of the atmosphere, in order to discover their properties, at the temperatures at which they may be expected to be used under the ordinary conditions of working. Examples of such are to be found in copper and bronze firebox stays for locomotives, and steel which is to be used for boiler making. These are cases of parts of structures exposed to high temperatures ; the axles of railway vehicles are to some extent affected by exposure to frost, and tests of these at temperatures below the normal have been made.

141. High and Low Temperature Tests.—It is known that many metals, when exposed to temperatures much above the normal, are affected to a considerable extent as regards their strength properties. The gradual increase in the pressures, and consequently the temperatures at which steam boilers are worked makes the testing of metals at high temperatures most important.

The objects to be aimed at in carrying out a test of this kind satisfactorily are :—

(*a*) The application and measurement of the loads on the test bar.

(*b*) The maintaining of the bar at a uniform and prearranged temperature during the whole of the test.

(*c*) The provision of means for reading this temperature.

(*d*) The provision of means whereby the extensions of the bar can be ascertained during the test.

The same are true for low temperature tests.

The application and measurement of the load is effected in the usual way, in some cases the holding shackles being attached to the test piece outside the heating apparatus, while in others the test bar is attached to the ends of two special bars which themselves pass into the heating bath.

In order to maintain the bar at the required uniform temperature the usual plan adopted is to have it immersed in a bath of some liquid which can be kept at any desired temperature. The liquid used may be oil of high flashing point, if the required temperature is not to be above about 570 deg. Fah.; while, for higher temperatures, an alloy must be used, such as one consisting of tin and lead.

The temperature of the fluid in which the test bar is immersed, and consequently of the bar itself, may be measured by means of a high temperature mercury thermometer. Up to a temperature of about 600 deg. Fah. the ordinary type of thermometer may be used, but for temperatures beyond this a thermometer having compressed nitrogen above the mercury column is necessary.

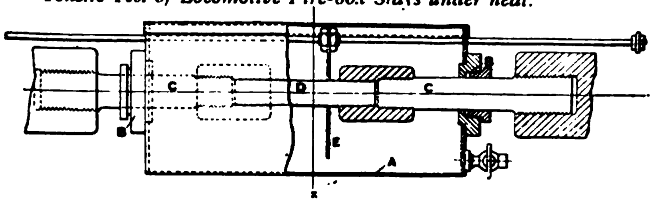
Where extensions of the test piece are to be taken during the progress of the test, two measuring pieces must be attached to the bar, one at each end of the measured portion, these pieces protuding from the liquid and the measurements taken direct from them, it being assumed that two points on these are separated to precisely the same extent as the two points on the bar itself. As the specimen will contract laterally as well as extend under the load, the measuring pieces must be attached to the bar through spring clips so as to compensate for the contraction.

One form of vessel for maintaining a test bar at a high temperature during a tensile test is shown in section on Fig. 130.* This is the apparatus used for testing firebox stays at the Midland Locomotive Works, Derby. The testing machine is here a horizontal one, made by Messrs. Whitworth. In the figure the bar which is being tested is marked D, and it is connected to the shackles of the machine through two bars C C. These pass into the heating tank A, through two stuffing boxes B B, so that there can be no escape of the fluid from the box, and at the same

* Proc. Inst. Mech. Eng., 1898.

time allowance is made for tbe free extension of the bar during the test. The casing is filled with a mineral oil having a high flashing point, this oil being maintained at the required temperature by means of a Bunsen burner placed under the casing. In this arrangement there is no provision for measuring the stretch of the bar during the test, but there would be no difficulty in attaching two small projecting pieces from which the measurements could be taken. In order to preserve the temperature uniform throughout the oil, a perforated stirrer, E, is provided.

Tensile Test of Locomotive Fire-box Stays under heat.



Transverse Section on line X

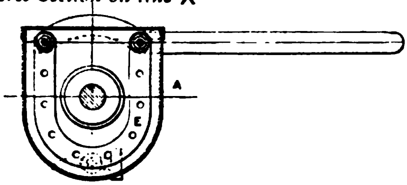


FIG. 130.

For testing of this kind a horizontal machine is much better than one of the vertical type, because it is much more easy to maintain the fluid at the required temperature, when the source of heat can be applied beneath the vessel than when the heat has to be applied through the walls of a vertical vessel, and, moreover, less difficulty is experienced in maintaining a fluid-tight joint, where the bar or the holding shackle passes into the vessel. It is also more convenient to work with a permanently fluid substance, such us mineral oil, than to have to make use of an alloy of lead and tin, which, of course, becomes solid at the normal temperature. Where an alloy of this kind has to be used it will be necessary to melt it in a separate vessel,

and to pour it into the casing when the test bar has been placed in position for the test. When the test is complete the alloy must be poured out again before it has time to solidify. Owing to the fact that there is little free convection of the fluid in the case of an alloy, it is not easy to preserve a uniform temperature at all points.

For low temperature tests, a freezing mixture must be used in place of the hot fluid.

Experiments were made on the effect of temperature on the strength of metals as long ago as 1856, by Sir William Fairbairn, who tested iron for boiler plates and rivets at temperatures varying from 30 deg. Fah. to 435 deg. Fah.* These tests were carried in an extemporised vertical testing machine of the single lever type. The specimens tested were reduced in cross-section at the part exposed to the heating and cooling influences, so that fracture at that point was rendered certain. The rod coming from the lower shackle and attached to the lower end of the specimen was made to pass through the bottom of vessel containing the heating fluid, in the case of hot tests. In the box was a quantity of oil or water which was kept at the required temperature by means of a fire grate placed beneath and around it. The position of the test bar was such that the part upon which the test was to be made was immersed so as to be throughout the test kept at the temperature of the fluid. For the tests in which the temperature was maintained below that of the surrounding atmosphere, the hot liquid was replaced by a freezing mixture.

A number of tests have been more recently made by Mr. Thomas Andrews† on railway axles at both high and low temperatures. In the cases where these axles were tested whole under a falling load, they were first exposed for an hour to either the cooling action of a freezing mixture or to the heating effect of the warm bath. When an axle was to be tested it was immediately lifted out of the bath by means of a small crane, placed in position, and the test carried out at once. As the axles were relatively large masses of metal, and the test was carried out immediately after being lifted out of the bath, there was little change in temperature. The tests were carried out at two distinct temperatures, namely, the cold tests at 7 deg. Fah. and the warm tests at 120 deg. Fah. The freezing

* Brit. Asso. Report, 1856.
† Min. Proc. Inst. C.E., lxxxvii. and xciv.

mixture used by Mr. Andrews consisted of two parts by weight of snow or powdered ice and one part of salt, while the heating was effected by exposing the axles in a bath of warm water. In some more recent tests at Cornell University a bath of alcohol was used, into which was sprayed liquid carbonic acid, by which means a temperature as low as 70 deg. below zero Fah. could be maintained.

Experiments to the same end have been made by M. Knut Styffe, of Stockholm, Mr. Sandberg, Mr. Webster,* at

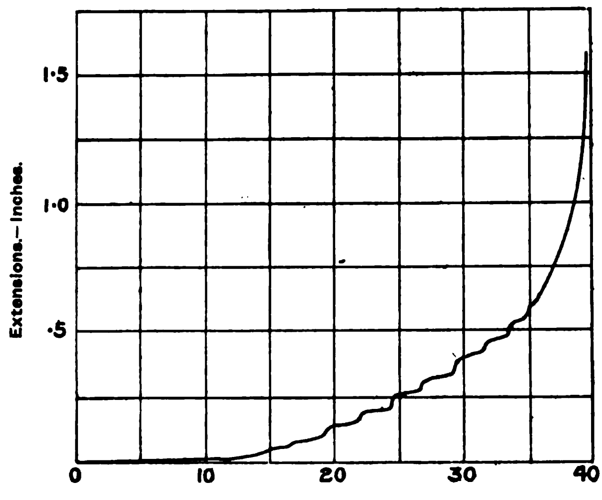


FIG. 131.—Load Strain Diagram for Steel Bar, Tested at 650 deg. Fah.

the Watertown Arsenal, the Berlin Testing Laboratory, and a number of other laboratories. The published results of these tests accord fairly well, and show that wrought iron after slightly decreasing in strength to about 250 deg. Fah. reaches a maximum of strength at about 500 deg. Fah., and from this point steadily decreases in strength as the temperature is further increased. Steel exhibits much the same properties, reaching a maximum of strength at somewhere about 500 deg. Fah. Copper and the bronzes decrease in strength continuously as the temperatures are increased.

The effect of a high temperature on wrought iron and steel bars under a tensile test is curious as regards the extensions. Whereas, at the normal temperature, the

* Min. Proc. Inst. C.E., lx.

extensions take place steadily and gradually, producing a smooth load-strain curve, it is noticed that at certain high temperatures the extensions take place suddenly, in jerks, and the free end of the weighing beam of the machine is seen to drop on to the lower stop and remain there for a few moments, as if the maximum load had been reached, when it is again seen to be raised and the bar carry the load as before. On the extensions being measured during the test in the usual way and a diagram plotted, this will have the form indicated on* Fig. 131. As iron and steel have a maximum strength at about 500 deg. Fah., and if a bar of one of these metals is tested to destruction at about this temperature, it follows that the bar always breaks at a point outside the fluid, that is, if the bar is parallel in form.

The following tables of flashing points of a number of oils and melting points of alloys may be useful in selecting a suitable one for the heating bath :—

Oils.	Flashing Points. Deg. Fah.
Cotton seed	550 to 565
Lard	570 ,, 585
Rape	565 ,, 580
Olive	550 ,, 565
Castor	535 ,, 545
English mineral	350 ,, 400
American ,,	340 ,, 390
Russian ,,	323 ,, 389
Scotch ,,	300 ,, 350

MELTING POINTS OF ALLOYS OF TIN AND LEAD.

Tin. Parts by Weight.	Lead. Parts by Weight.	Melting Point. Deg. Fah.
150	100	330
100	100	370
57	100	420
50	100	440
33	100	480
25	100	500
16	100	520
10	100	540
4	100	560

* Johnson's "Materials of Construction."

The writer has found the alloy of equal parts of lead and tin, by weight, melting at 370 deg., to be a convenient mixture. When an alloy is used, a mercury thermometer may be used for the temperatures, the thermometer being kept in the fluid metal, and the temperature noted frequently, and at various points. Care must be taken that the metal is not allowed to solidify when the thermometer is in it.

THE TESTING OF CHAINS.

142. In no branch of engineering constructive work is careful and thorough testing of more importance than in the case of chains. This is due partly to the fact that in many cases the failure of a chain may be attended with injury to, or loss of, human life, and also because chains

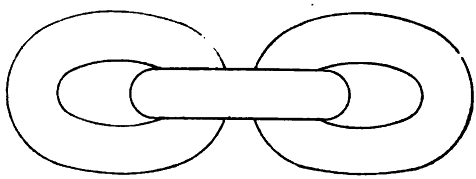


FIG. 132.—Short Link Chain.

are made up of a number of separate parts, each of which contains a joint, and the fracture of any one of these separate pieces will probably cause the failure of the whole chain. The kind of chain which is most frequently used for haulage and lifting purposes is the ordinary "short link" iron welded chain; a sketch of one of the links of a chain of this kind is shown on Fig. 132. The

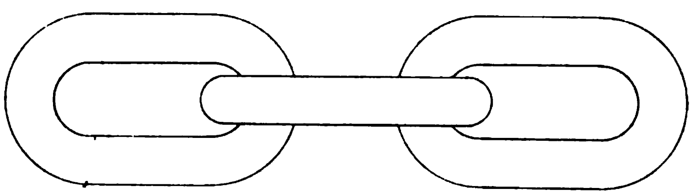


FIG. 133.—Long Link Chain.

proportions of these links are as follow: The total outside length is four and a half times the diameter of the iron forming the link, and the greatest outside width is three and a quarter times the diameter. There is also the long link chain, shown in Fig. 133. For some purposes the

stud-link chain is used. Besides these there are a number of smaller chains, such as the "single jack," "double jack," and the American "Triumph" chain (shown respectively at A, B, and C, Fig. 134), all of which have their special uses.

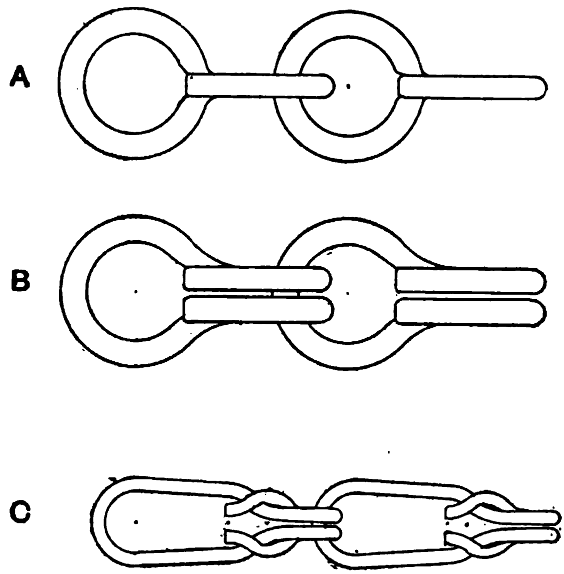


FIG. 134.—A, Single Jack Chain ; B, Double Jack Chain ; C, "Triumph" Chain.

The chains which most frequently have to be tested are the ordinary short link welded and the long link chains. The tests to which a chain is subjected are as follow :—

(*a*) Tests require to be made of the material of which the chain is composed, in the form of bars. These tests are simply tension tests carried out in the ordinary way. The results required are the *maximum stress*, the *percentage elongation on a given length*, and the *reduction in area.*

(*b*) Breaking tests of a given specified length of the finished chain, often on 36 inches. The measurements taken are the *breaking load*, and the *extension on the given length* before fracture occurs.

(c) The chain as a whole is also tested up to some specified proof load, the extension under this proof load being measured.

The two first-mentioned of these tests are usually carried out in an ordinary testing machine, while the tests under proof loads are made in tension machines specially designed to accommodate pieces of chain of considerable length.

There is no difficulty about holding a chain specimen in the machine. In the absence of special holders a piece of bar iron or steel a little larger than the material of the chain may be bent hot into a U shape, threaded through the end link of the sample, and gripped by the ordinary wedge dies which are used for flat specimens. This is a simple and perfectly effective method of holding the ends of the short length of chain. The arrangement

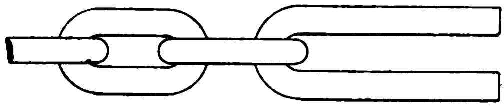


FIG. 135.—Holder for Chains.

is shown on Fig. 135. Extensions are measured between two centre-punch marks placed respectively on the middle of each of the outside links of the length to be measured, the actual measurements being made with a pair of trammels or beam compasses.

When a short length of chain is tested to destruction the links become elongated after the elastic limit of the metal has been passed, and failure generally takes place by the breaking of one of the links at an end, where the curvature is greatest, and most likely at the point where the weld is. Before actual fracture takes place many of the links begin to show signs of weakness, this being most noticeable in tbe partial opening of the welds. The elongation is often measured at the proof load, and also at the maximum load, and the elongation due to the increase of load between these points quoted in the report.

The testing of chains under the specified proof loads is generally carried out on long pieces of the actual chain, the loads applied not being such as to permanently damage it, but at the same time being sufficient to bring to light any defects which may exist either in the material of the chain or in the weld joints of the links. For instance,

the proof stress insisted upon by the Admiralty is that the chain shall be subjected to a stress of 7·65 tons per square inch of the total cross section of the link. If the chain is made from 1 in. iron, the area of cross section of the link is 1·57 sq. in., which gives a total proof load of 7·65 by 1·57, or 12 tons. When the proof load has been put upon the chain every link is carefully examined in order to find out if any of the joints have shown a tendency to open, or whether the metal has exhibited any flaws or signs of weakness. Tests of this kind are carried out in special machines. One of these, made by Messrs. J. Buckton and Co., is precisely similar in principle to the horizontal compound lever machine by the same makers, Fig. 34, p. 85. In the case of the chain tester the frame G is replaced by a cast-iron trough 88 ft. long and 2 ft. wide. One end of the chain to be tested is attached to the crosshead, which is linked to the short end of the lever by the

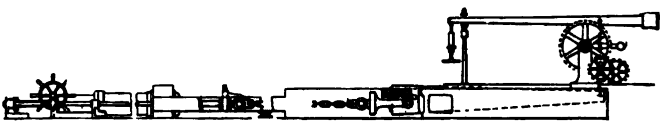


FIG. 136.—Buckton's 250-Ton Chain Tester.

links K. The attachment is made by means of a pin slipped through the last link of the chain. The other end is fastened to the crosshead H, fixed at some point in the trough, according to the length of chain to be tested. The capacity of this machine, which is in use at the Horwich Locomotive Works, is 100 tons, and the greatest length of chain which can be tested is 82 ft., and the shortest 4 ft.* A machine of larger capacity, supplied by Messrs. Buckton to the British Admiralty, is shown on Fig. 136. This machine is capable of testing a cable up to a length of 90 ft., and to a load of 250 tons. The gearing to the right is for testing shafts in torsion up to 3 in. diameter, and at a load of 300,000 inch pounds.

Another machine of smaller capacity, and portable, is shown on Fig. 137. One end of the chain is fixed to a movable crosspiece between the two girders shown, and the other to the right-hand crosshead which is linked to the hydraulic ram. The water under pressure is supplied by a hand-pump, and the load upon the specimen is indicated by a pressure gauge. The

* *Engineering*, October 9th, 1891.

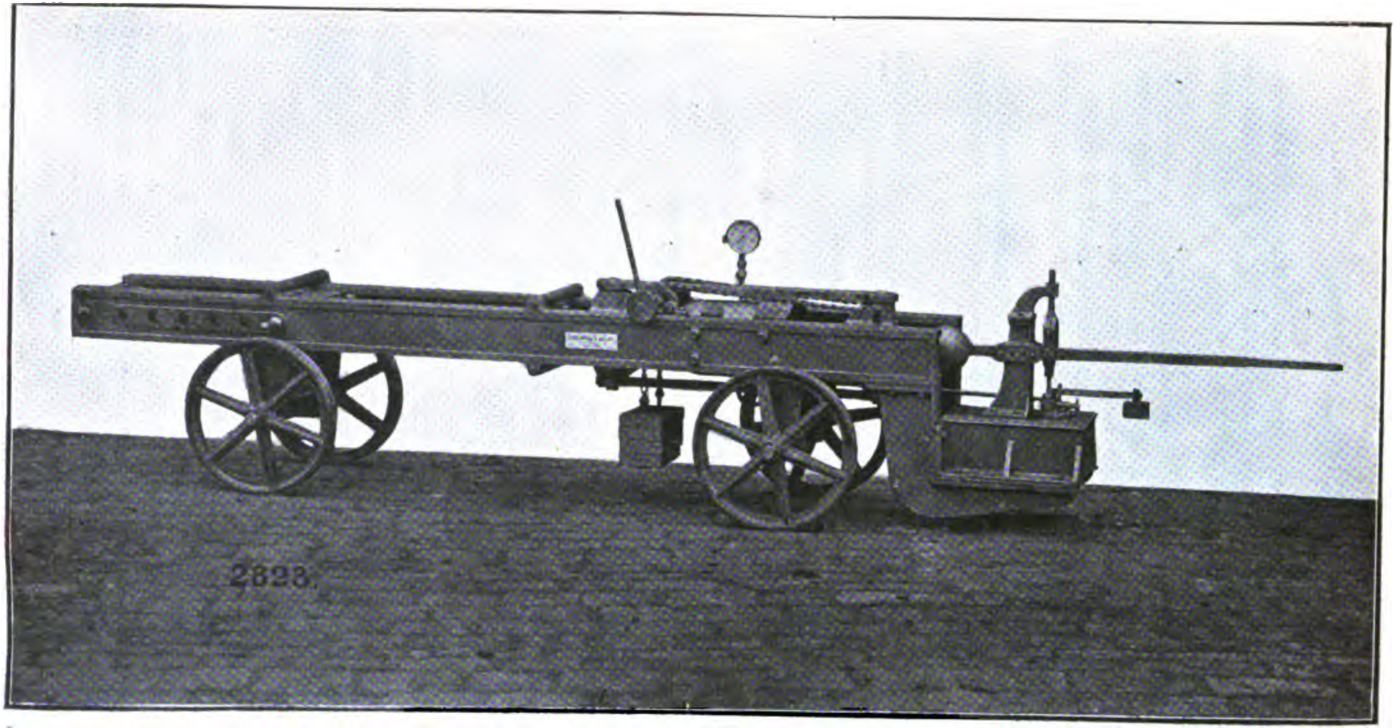


FIG. 137.—Greenwood & Batley's Chain-Testing Machine.

maximum load which this machine is capable of is 100,000lbs., and it will test chains up to 5ft. long and 1in. diameter. The machine is made by Messrs. Greenwood & Batley.

In some cases, in addition to the tests which have been mentioned, links are cut from the chain, opened, and straightened under heat, and afterwards tested as bars in the usual way. After the inspection under the proof load any defective links should be taken out of the chain and replaced by sound ones.

The following is an example of a complete test of a 1in. iron chain intended to be used for lifting purposes :—*

	Test of the Bar Iron.			Test of a 36in. Length.			Proof Load.
Diameter.	Max. stress. Tons per sq. in.	Elongation on 4in.	Reduction in area.	Breaking load. Tons.	Breaking stress. Tons per sq. in.	Elongation on 36in.	Tons.
1in.	23	30 %	48 %	31·8	19·1	8¼in.	12

TESTS FOR HARDNESS.

143. The hardness of a metal may be best described as the resistance which the particular metal offers to permanent strain or plastic deformation, it being understood that brittle metals, such as cast iron, do not come within this definition. Various means have been employed by which to determine the relative hardness of different substances. Of these, some of the earliest methods employed were made to depend, either upon the possibility of one substance being able to produce a scratch upon some other substance, or upon the relative ease with which a standard substance would produce a scratch upon the material in question. Another kind of test for hardness is made to depend upon the volume of a standard body which can be forced into the surface of the given material by the application of a standard load for a given length of time. In the method used by Col. Rodman, of the United States, the quantity of material displaced by the expenditure of a standard quantity of mechanical work in forcing a hard steel diamond point into the material to be tested was

*Engineer, October, 1898, p. 365.

measured. By this means a scale of relative hardness was determined. The work done in causing the point to penetrate the metal was obtained from a falling weight. This method was also employed by Lieut.-Col. Martel, who has obtained the following values for the relative hardness of a number of metals:—

TABLE OF RELATIVE HARDNESS ACCORDING TO THE MARTEL SCALE.

Metals.	Relative Hardness.
High carbon steel, hardened	613
High carbon steel, not hardened	460
Medium steel, hardened	455 to 300
Rolled wrought iron	226
Cast iron	300 to 208
Bronze, cast in sand	137
Copper, rolled	156
Copper, annealed	64
Tin, cast	33
Lead, cast	9

A convenient form of test for hardness, also depending upon the indentation of the material, has been devised by Professor Unwin.* In Unwin's test, an indenting tool of hard steel having the form of a knife edge is used, and the indention is produced by a steady load on a short bar of the metal to be tested. Provision is made for the measurement of the amount of the linear indentation produced by a series of loads, and from these observations a constant is determined which is taken as the measure of the hardness of the metal.

On Fig. 138 is shown the arrangement of the apparatus used by Professor Unwin. This consists, in the first place, of the two blocks marked respectively A and B. Of these, A is a plunger loosely fitting into the cast-iron block B. The whole rests between the compression plates of the testing machine, by which the plunger is forced downwards. At the lower surface of the plunger is a triangular groove forming the seating in which rests the indenting tool C, which consists of a short piece of square steel, hardened and ground. The test-piece is marked C in the figure, and usually consists of a piece of the material 2½in. long and ⅝in. square. By means of the vernier and scale shown, the relative movement of the plunger and the base block can be measured to 1,000th of

* Min. Proc. Inst. Civ. Eng. Vol. CXXIX., p. 334.

an inch. A careful determination of the compression of the apparatus itself under different loads makes it possible to take the relative movement of the plunger and the block, minus this compression, as the amount of linear indentation or penetration of the tool into the test-piece. From a series of preliminary tests Professor Unwin found

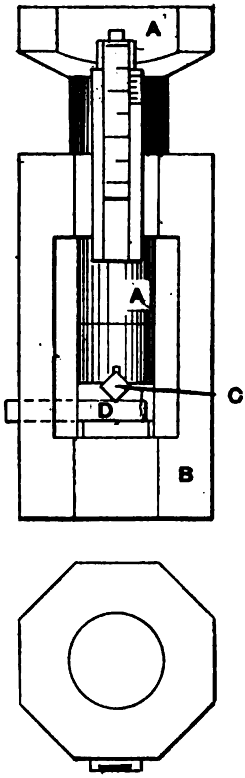


FIG. 138.—UNWIN'S GEAR FOR HARDNESS TESTS.

that the relation existing between the indentation and the load producing it is expressed by an equation of the following form:—

$$Ci = p^{1 \cdot 2}$$

where i is the depth of the indentation in inches, p is the pressure per inch width of the knife edge producing the indentation, and C is a constant depending upon the

material tested. This value is taken as the measure of the indentation hardness of the metal tested. Writing this equation in the form

$$C=\frac{p^{1\cdot 2}}{i},$$

it will be seen that p and i can be measured during the test, the index 1·2 being practically constant for all ductile metals.

The actual value of this index was found by Professor Unwin by plotting curves showing the relation between the logarithms of the indentations and the logarithms of the loads per inch of width of the indenting tool, and finding the slope of the straight line, which form the curve takes. By using this test Unwin has made it possible to make actual quantitative tests of the hardness of

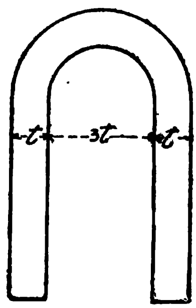


Fig. 139.
Admiralty Hardening and Cold Bending Test.

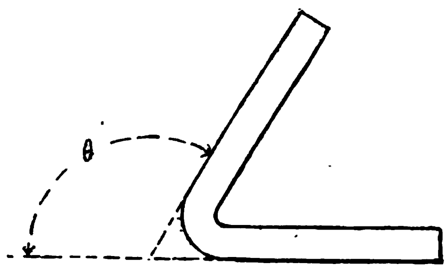


Fig. 140.
Admiralty Hot Bending Test for Wrought Iron.

various metals, in the place of simply establishing scales of relative hardness. The following is a table of some of the values obtained :—

Hardness.

Metal.	Values of C.
Cast steel, normal	554·0
Mild steel, normal	143·5
Copper, annealed	62·0
,, unannealed	105·2
Brass, No. 1	221·0
,, No. 2	246·0
Aluminium, squirted	41·8
,, alloy, cast	103·5
Lead, cast	4·2
Zinc, cast	40·8

SHOP TESTS OF IRON AND STEEL.

144. In addition to the tensile, compressive, and cross-breaking tests which have been described, the purchasers of iron and steel for structural purposes are in the habit of insisting upon certain other tests being undergone by samples of the metal. These further tests are such as can be carried out without the help of any special machinery by means of ordinary appliances such as are available in any forge. Many of these tests are also insisted upon by such authorities as the Admiralty, Lloyd's, and the Board of Trade. These include hot and cold bending tests, drifting tests, drop tests, and smithy tests.

145. **Cold Bending Tests.**—There is no more useful test applied to wrought iron and steel than the bending test. It is easily and quickly performed, and it can be carried out in the manufacturer's works. This

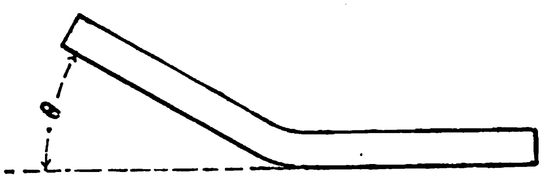


FIG. 141.—ADMIRALTY COLD BENDING TEST FOR WROUGHT IRON.

test must not be confused with the cross-breaking tests which have already been described. It consists in simply bending a strip of the materal, either until fracture takes place—and at the same time noting the angle to which it has been bent—or in bending the strip through a specified angle, to a certain radius of curvature, and noting whether or not the outer fibres have shown any tendency to crack or fracture. If the material is satisfactory from the point of view of this test, there should be no such cracking of the metal. The actual testing may be effected best by means of an hydraulic press, the bending being made over a mandrel of given diameter, or a steam or sledge hammer may be used, preferably the former. Bending under a gradually applied force is far more satisfactory than bending under blows. In some cases screw vices are used.

Unfortunately these tests are not sufficiently standardised to make them very useful in applying a rigid

comparison to metals by different makers, each authority having its own particular requirements. In these tests no load is measured, as they are simply for the purpose of ascertaining the ductility and endurance.

As illustrating what kind of requirements are specified, it may be stated that the rules laid down by the British Admiralty are as follow: Test for—

Steel Plates.—"Strips cut lengthwise of the plate, $1\frac{1}{2}$in. wide, heated uniformly to a low cherry red, and cooled in water at 82° Fah., must stand bending in a press to a curve of which the inner radius is one and a half times the thickness of the plated tested." This heating and

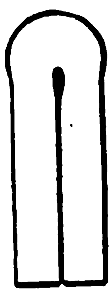


FIG. 142.
BEST WROUGHT IRON AND MILD STEEL, BENT CLOSE.

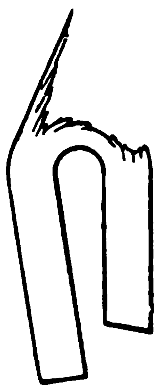


FIG. 144.
NICKING AND COLD BENDING TEST.

quenching is to discover if there is any tendency to harden.

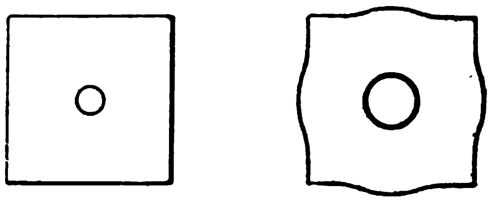
Lloyd's rule also says: "Strips cut from plate, angle, or bulb steel to be heated to a low cherry red, and cooled in water of 82° Fah., must stand bending double round a curve of which the diameter is not more than three times the thickness of the plates tested." See Fig. 139. The Board of Trade requirements are the same.

Iron Plates.—For iron plates the Admiralty test is as follows: Hot, to be bent from 90° to 125°, without fracture, as in Fig. 140: in this figure and the next one

the angle is denoted by θ. Fig. 141: Cold test, to bend without fracture to the following angles:—

		Lengthways.		Crossways
1in. plate	....	10 to 15 deg.	....	5 deg.
$\frac{3}{4}$in. ,,	....	20 to 25 ,,	....	5 to 10 ,,
$\frac{1}{2}$in. ,,	....	30 to 35 ,,	....	10 to 15 ,,
$\frac{1}{4}$in. ,,	....	55 to 70 ,,	....	20 to 30 ,,

The same plan is adopted by private purchasers, and in the case of both iron and steel plates and bars it is usual to specify that a specimen of required size must be able to stand bending back upon itself—that is, through 180° over a bar of certain radius, generally one and a half times the thickness of the plate or bar, without showing any signs of cracking. In some cases specimens from steel plates and bars are bent close upon themselves—that is, with no internal radius of curvature at



BEFORE. AFTER.

FIG. 143.—DRIFTING TEST.

the bend, without signs of cracking, Fig. 142. If the specimen begins to crack at a less angle than the specified one, which may not be necessarily 180°, the angle at which this takes place is noted and given in the report.

146. Drifting Tests.—A good test often applied to mild steel is that of drifting out a hole of specified size to one much greater. When this is done, any lack of ductility is at once shown by the cracking of the edges of the hole so drifted. A usual drifting test is to punch or drill a hole $\frac{5}{8}$in. diameter in a piece of the metal 4in. or 6in. square, and enlarge this hole by forcing in a circular drift with a ten-to-one taper until the hole has been enlarged to $1\frac{1}{2}$in. diameter. This is seen on Fig. 143. When tested under these conditions, if the metal is not sufficiently ductile, either the plate will be split clean across or small local cracks will appear around the edges of the hole.

147. Drop Test.—This is a test to which steel rails and steel tyres are subjected. When applied to steel rails it consists in supporting the 24ft. length of the rail on bearings 3ft. apart and situated at equal distances from both ends. A cast-iron weight of half a ton is raised to a height of 15ft. above the rail, and allowed to fall on its middle. The effect of this blow is to produce a certain amount of permanent set in the form of deflection, and this is not supposed to exceed a certain amount for the first blow, such as 2½in.

A similar test is applied to steel tires for rolling stock. The tire is allowed to rest between supports and a weight of one ton allowed to fall upon it. The drop is repeated from increasing heights until a specified deflection is produced. This may be two inches for every foot of its internal diameter.

148. Smithy Tests.—Many useful tests are made upon wrought iron and steel by the smith.

For wrought iron a common test is that shown on Fig. 144. Here the bar or strip is nicked and then bent, the fibrous or non-fibrous nature of the specimen being

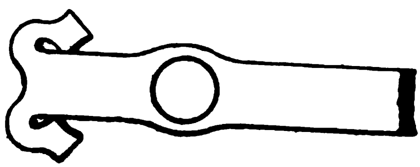


FIG. 145.—RAMSHORN TEST FOR IRON.

exhibited at the fracture. For good wrought iron the fracture should show a silky fibre. Another is the Ramshorn test (Fig. 145). Here the strip is split at the end and turned over, and also a hole is punched and drifted. This is done when the metal is hot.

Another test is to twist a strip through a certain number of turns without fracture. These are only a few of the many miscellaneous tests that are applied to bars, plates, and samples of sectional iron and steel, but they will serve to indicate in what direction these are carried out.

Chapter IX.

THE TESTING OF STRUTS OR PILLARS.

149. The testing of short cylindrical specimens in compression has already been described in detail. In the case of these, the ratio of $\frac{length}{diameter}$ is purposely made small, usually not exceeding 3 : 1, or, better still, 2 : 1, in order that failure may take place by crushing alone. Here the relation between the load and the stress developed in the material is a simple one :—

$$f_c = \frac{P}{A}$$

where f_c is the compressive stress per unit area, P the total load, and A the area of the cross-section. The most important point to be determined from such a test is the value of f_c, corresponding to the elastic limit in compression.

When the length of the specimen is increased much beyond the above limits, the relation between load and stress becomes less simple. Imagine a compression specimen in which the length is very great relatively to the diameter, say 200 to 1. If this is placed between the compression plates of a testing machine, and a load applied directly along its axis, common experience will indicate that, when the load has reached a certain value, the bar will begin to bend, and the deflection will continue to increase until the extreme fibres have passed their elastic limit, when collapse will rapidly ensue. These cases form the two extreme limits which are found to exist for compressive loading, that is, when the pillar is relatively short, failure takes place by crushing alone, the stresses due to bending being inappreciable ; while, in the second case, where the length is very great in proportion to the diameter, failure is due to the bending action, the stress caused by the crushing being negligible.

The actual conditions in what may be called pillars, or columns, or struts, in practice, such as the struts in framed structures, connecting rods, and pillars in buildings, lie between the two limits which have been indicated. Various formulas have been devised to meet the case.

For *short pillars*, the formula is—

$$P = f_c A$$

For *very long pillars*, where the ratio of length to diameter is greater than 150 to 1, the true relation is given by Euler's Formula*, which is as follows :—

$$P = \frac{\pi^2 E I}{l^2}$$

* PROOF OF EULER'S FORMULA.

In Fig. 146, A D B represents the axis of a strut, carrying a load P, originally applied in an axial direction, and causing the pillar to be deflected at its centre D an amount δ.

Let y be the deflection at any point O. At O

$$M = -Py \quad \text{(see "Deflection of Beams")}$$

$$= \frac{EI}{R}$$

$$= EI \frac{d^2y}{dx^2},$$

therefore, $$\frac{Py}{EI} = -\frac{d^2y}{dx^2}.$$

Now, integrate, $$\frac{Py}{EI}\frac{dy}{dx} = -\frac{dy}{ax}\frac{d^2y}{dx^2}$$

$$\frac{P}{EI}\frac{y^2}{2} = -\frac{1}{2}\left(\frac{dy}{dx}\right)^2 + C$$

putting $$\frac{dy}{dx} = o,\ C = \frac{P}{EI}\frac{\delta^2}{2}\ y = \delta.$$

Therefore, $$\frac{P}{EI}\left(\delta^2 - y^2\right) = \left(\frac{dy}{dx}\right)^2, \quad \text{or}$$

$$= \sqrt{\frac{P}{EI}}\,dx = \frac{dy}{\sqrt{\delta^2 - y^2}}$$

Integrating again, $$x = \sqrt{\frac{EI}{P}}\,Sin^{-1}.\ \frac{y}{\delta} + A,$$

when $$x = o,\ y = o, \quad \text{and}$$

therefore, $$A = o$$

So that $$x\sqrt{\frac{P}{EI}} = Sin^{-1}.\ \frac{y}{\delta}$$

or $$y = \delta\ Sin\left(x\sqrt{\frac{P}{EI}}\right).$$

this is the equation to the sinusoid, or elastic curve.

When $$x = \frac{l}{2},\ y = \delta,$$

so that $$o = Sin\left(\frac{l}{2}\sqrt{\frac{P}{EI}}\right);$$

that is to say $$\frac{l}{2}\sqrt{\frac{P}{EI}} = \frac{\pi}{2},$$

$$\frac{l^2}{4}\frac{P}{EI} = \frac{\pi^2}{4},$$

or $$P = \frac{\pi^2 EI}{l^2}$$

which is Euler's equation.

Here P is the collapsing or buckling load, E is the modulus of elasticity of the material, I is the moment of inertia of the section, and l the length of the strut. The meaning of the equation is that if P is greater than

$$\frac{\pi^2 EI}{l^2}$$

the strut will collapse.

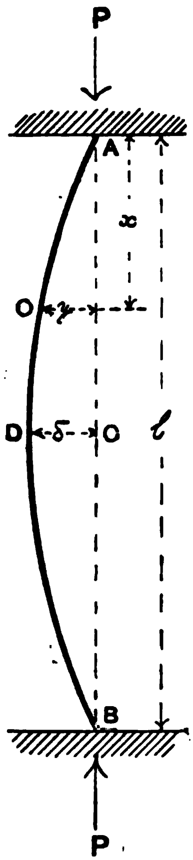


Fig. 146.

In the above form, it refers to a pillar which is *rounded* or *hinged* at the ends. (See Figs. 146 and 147.)

If the pillar is *fixed* at the *two* ends the formula becomes (Fig. 148)

$$P = \frac{4 \pi^2 E I}{l^2};$$

and, if fixed at one end and rounded at the other (Fig. 149)

$$P = \frac{2 \pi^2 E I}{l^2}$$

When the pillar assumes more nearly the proportions usually met with in practice, it fails by combined crushing and bending, and neither of these extreme formulas holds.

In this case consider a pillar, Fig. 147, of length l, pivoted or free to revolve at the ends, and subjected to a compression load, P. The load will induce a compressive stress in the material, f_c, such that

$$f_c = \frac{P}{A}$$

A being the area of the cross-section of the pillar.

The pillar will also be bent under the load, this bending being immediately caused by the bending moment represented by the product of the load on the column P, and the deflection, δ, which it maintains. It is conceivable that if the load could be applied truly along the axis of the pillar, and there existed no inequalities in the material, no flexure would be produced, and failure would take place by crushing. This state of things is not possible of attainment, the pillar being in a state of unstable equilibrium; the load is never quite axial, the axis is not perfectly straight, and there are always small inequalities in the material. So that there is a bending moment on the pillar from the time the load first comes on. As the load increases, the deflection increases with it, and, therefore, the moment also, both by reason of the increase of load and of the increase of the deflection, so that the bending moment increases more rapidly than in the simple ratio of the increase of load.

This continues until the maximum stress in the material exceeds the elastic limit stress. Various formulas have been constructed to express the relation between the dimensions of pillars and the loads required to produce

collapse. Of these, Euler's formula, deduced from theoretical considerations, is true only for long struts, whose ratios of length to diameter are much beyond what exist in practice. On the results of the experiments of Eaton Hodgkinson, Gordon based his well-known formula; Rankine modified Gordon's formula and reduced it to a form which is more generally applicable; Johnson has devised what he calls a parabolic formula; and besides the classic experiments of Hodgkinson, those of Christie, Davies, and later of Considère and Tetmajer have contributed to the determination of the empirical constants used in these formulas.

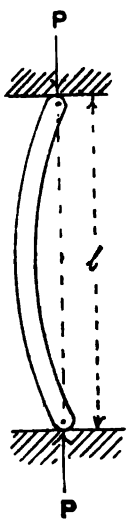


FIG. 147.

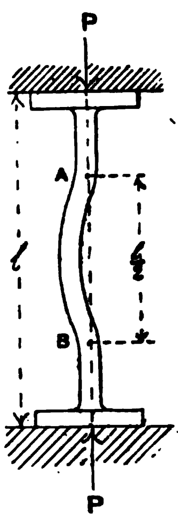


FIG. 148.

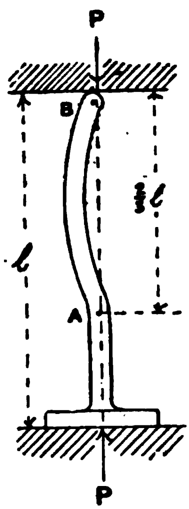


FIG. 149.

It will suffice here to indicate the process of reasoning leading up to Rankine's formula.

The pillar, under an axial load P, may be held in position in one of three different ways.

In Fig. 147 the pillar, of length l, is provided with rounded ends or hinges, so that there is no constraint. The length l is the effective length, and is between the outsides of the rounded ends or between the centres of the pin joints.

In Fig. 148 the pillar is shown as being provided with feet, by means of which the ends are constrained and

prevented from being deflected. At A and B are what are called the points of "contrary flexure," the part between A and B being in exactly the same condition as the pillar in Fig. 147. The length of this portion is one-half the total length of the pillar. The same conditions are attained if the ends are built in or fixed in any other way, so long as movement is prevented.

The third case is shown in Fig. 149. Here the pillar is fixed at one end and free at the other. The point of contrary flexure is at A, the length A B being two-thirds the total length.

First consider the case of Fig. 146. Let f_c be the uniform compressive stress on a cross section of the pillar due to the pressure caused by the load alone. This will be

$$f_c = \frac{P}{A},$$

where A is the area of the section in square inches.

Again, let f_b be the maximum stress on the concave or compression side of the pillar. Here

$$\frac{f_b}{Y} = \frac{M}{I}$$

(see "Deflection of Beams," par. 14, p. 34).
Or,

$$f_b = \frac{M Y}{I}.$$

But $M = P . \delta$, where δ is the deflection of the middle of the pillar from the vertical, and

$$\delta \propto \frac{M . l^2}{E I}.$$

So that, substituting,

$$f_b \propto \frac{P M l^2}{E I} \cdot \frac{Y}{I} \propto \frac{P l^2}{E I}$$

in this expression, E, the modulus of elasticity, is constant for a given material; and I, the "moment of inertia" $= A k^2$, where k is the radius of gyration. So that, if C is a constant only depending on the material—

$$f_b = C \frac{P . l^2}{A k^2};$$

if the total maximum stress be called f, then—

$$f = f_c + f_b = \frac{P}{A} \times C \cdot \frac{P}{A} \cdot \frac{l^2}{k^2}$$

which, written otherwise, becomes—

$$P = \frac{A f}{1 + C \cdot \frac{l^2}{k^2}}$$

which is Rankine's formula, f being the elastic limit stress in compression for the material in question.

Here the constant C only depends on the f and E of the material. In Gordon's formula, which is similar in form, the smallest diameter, d, takes the place of k, the constant varying with the section as well as the material.

It is as follows, the notation being the same as before, except that d is the least diameter of the column :—

$$P = \frac{A f.}{1 + a\left(\frac{l}{d}\right)^2}$$

Bovey* gives the values of f in this formula as 80,000 for cast iron, 36,000 for wrought iron, 67,200 for mild steel, and 114,000lbs. per square inch for hard steel ; and the values of the constant a :—

Kind of Section.	Cast Iron.	Wrought Iron.	Mild Steel.	Hard Steel.
Solid Rectangular	$\frac{1}{450}$	$\frac{1}{3000}$	$\frac{1}{2000}$	$\frac{1}{1400}$
,, Round	$\frac{1}{400}$	$\frac{1}{2250}$	$\frac{1}{1400}$	$\frac{1}{900}$
Hollow Rectangular ...	$\frac{1}{500}$	—	—	—
,, Round	$\frac{1}{800}$	$\frac{1}{5500}$	$\frac{1}{2500}$	$\frac{1}{1500}$

In Gordon's and Rankine's formulas l is the length of the pillar between the supports. If L is the length of a pillar with rounded or free ends, and l is the length of a pillar of similar material and section, but fixed at both ends, then for the two buckle under the same load

$$l = 2 L ;$$

and for the case of a pillar *fixed* at one end only and rounded at the other,

$$l = \frac{3}{2} L$$

These relations will be clear from an inspection of Figs. 147, 148, and 149. Rankine's formula for the three cases then becoming :—

Both ends rounded, $$P = \frac{A . f}{1 + C \frac{l^2}{k^2}}$$

* Bovey, "Strength of Materials."

Both ends fixed,

$$P = \frac{A \cdot f}{1 + \frac{C\,l^2}{4\,k^2}}$$

One end fixed and one, rounded

$$P = \frac{A \cdot f}{1 + \frac{4}{9} C \frac{l^2}{k^2}}$$

The values of f and C are variable to some extent for a given metal, but the following values given by Rankine and others may be expected to give results which are not very far wrong:—

Materials.	f Pounds per sq. in.	f Tons per sq. in.	C
Cast iron.........	8,000	35·75	$\frac{1}{1600}$
Wrought iron...	34,000 to 38,000	15·00 to 17·00	$\frac{1}{12000}$ to $\frac{1}{18000}$
Mild steel	67,200	30·00	$\frac{1}{5600}$

150. Johnson's Parabolic Formula.—On Fig. 152 are plotted curves representing graphically the three formulas of Euler, Rankine, and Johnson when applied to wrought iron pillars. Ratios of l to k are abscissæ, and buckling stresses in pounds per square inch are plotted as ordinates.

For Euler's curve, the buckling stress

$$\frac{P}{A} = \pi^2 . E . \left(\frac{k}{l}\right)^2$$

E being taken as 30,000,000lbs. per square inch.

For Rankine's curve,

$$\frac{P}{A} = \frac{f}{1 + C\left(\frac{l}{k}\right)^2}$$

f, the "elastic limit" stress in compression, being taken as 36,000lbs. per square inch, and C as $\frac{1}{12,000}$.

The third curve is that of Professor Johnson. It is parabolic in form, and is tangent to Euler's curve. The general form of Johnson's formula is

$$\frac{P}{A} = f - a\left(\frac{l}{k}\right)^2$$

U2

where f is, as before, the elastic limit stress in compression of the material, and a is a constant whose value is

$$a = \frac{f^2}{4\pi^2 E}$$

This value of a is dependent on the fact that the curve is tangent to that of Euler. Johnson* has found that this agrees very well with the plotted results of tests. Here $f = 36{,}000$lbs. per square inch and

$$a = \frac{(36{,}000)^2}{4\,.\,\pi^2.\ 30{,}000{,}000} = 1{\cdot}08$$

Professor Johnson gives the following as reliable average values:—

For wrought-iron columns, pin ends,

(where $\frac{l}{k}$ is not greater than 170)

$$\frac{P}{A} = 34{,}000 - 0{\cdot}67\left(\frac{l}{k}\right)^2$$

For wrought-iron columns, flat ends,

(where $\frac{l}{k}$ is not greater than 210).

$$\frac{P}{A} = 34{,}000 - 0{\cdot}43\left(\frac{l}{k}\right)^2$$

For mild-steel columns, pin ends,

(where $\frac{l}{k}$ is not greater than 150)

$$\frac{P}{A} = 42{,}000 - 0{\cdot}97\left(\frac{l}{k}\right)^2$$

For mild-steel columns, flat ends,

(where $\frac{l}{k}$ is not greater than 190)

$$\frac{P}{A} = 42{,}000 - 0{\cdot}62\left(\frac{l}{k}\right)^2$$

For cast-iron columns, round ends,

(where $\frac{l}{k}$ is not greater than 70)

$$\frac{P}{A} = 60{,}000 - \tfrac{25}{4}\left(\frac{l}{k}\right)^2$$

For cast-iron columns, flat ends,

(where $\frac{l}{k}$ is not greater than 120)

$$\frac{P}{A} = 60{,}000 - \tfrac{9}{4}\left(\frac{l}{k}\right)^2$$

* Johnson's "Materials of Construction," p. 362.

151. Testing Columns.—During the test of a strut, as the load is increased the pillar is caused to deflect more and more until the stress in the external fibres, due to deflection and the simultaneous direct compressive load, carries the metal beyond its elastic limit. When this point is reached the deflection begins to increase very rapidly and complete collapse by buckling results.

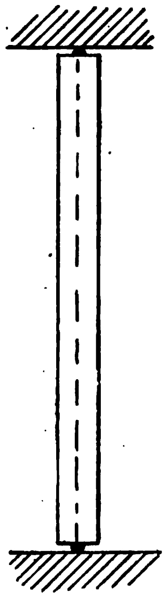


FIG. 150.

152. Fixing Struts in the Testing Machine.—The only really satisfactory way of holding struts in the testing machine is by having the ends hinged or rounded, that is to say, quite free to rotate. It is not usually convenient to attempt to fix the ends, and this cannot be done satisfactorily unless they are provided with very large feet, or firmly bolted down.

An easy and simple way of securing the freedom of the ends is shown in Fig. 150.

Here the ends are cut square, and two pieces of half- round steel are inserted as shown. These allow the ends to rock freely and effect the same purpose as rounded or hinged-ends. Care should be taken that the lines of contact coincide precisely with the neutral plane produced, as otherwise the load will be out of the centre. A better plan, but rather more elaborate, is shown in Fig. 151. This was first used by M. Considère, and also by Prof. Bauschinger and Prof. Tejmajer. The latter provide the ends of the struts to be tested with knife-edge or cone bearings, the edge of the knife edges or the apices of the cones being so placed so as to coincide with the geometric axis of the pillar, as far as could be judged, without any special means of adjustment.

M. Considère adopted the plan shown in Fig. 151. Here the ends of the strut are placed in sockets having double knife-edge bearings on the compression plates of the testing machine. The ends of the strut are to a small extent adjustable in the sockets by means of screws. In testing in this manner, before proceeding with the test proper, moderate loads are applied and the direction of

the deflection noted. The end of the strut is now moved by the screws in the opposite direction, this process being repeated until the deflection is reduced to a minimum under the loads applied. This brings the line of thrust of the load into approximate coincidence with the axis of the specimen, and the test may be proceeded with.

If knife-edge or conical sockets are used, the edges or pointed ends will penetrate the metal of the plates, and it

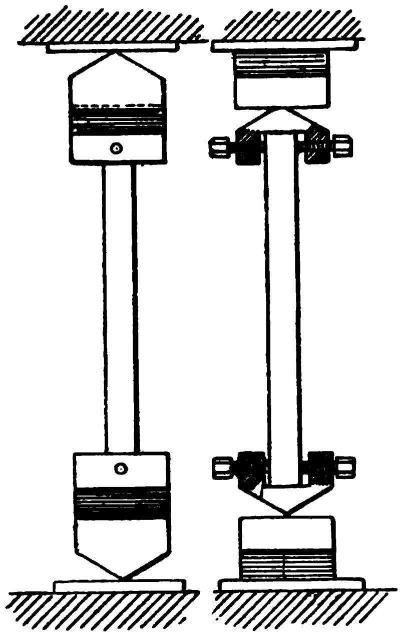


FIG. 151.

CONSIDÈRE'S METHOD OF HOLDING FOR STRUTS.

is therefore advisable to interpose two small steel plates between the edges or points and the plates of the testing machine.

153. Example of a Test of a Wrought-iron Column. The following sample of what may be expected to take place in a test of a column or pillar is based upon Tetmajer's Tests.

In the example given the column is of wrought iron, having an I section. The dimensions are:—

Depth of section = 6in.
Breadth of flanges = 4in.
Mean thickness of metal = $\frac{1}{2}$in.
Length between knife edges = 5·46ft.

The moment of inertia of the section about an axis through the centre of the web works out to $I = 5\cdot38$, and the area of the cross section $A = 6\cdot5$ square inches.

The (radius of gyration)^2

$$k^2 = \frac{I}{A}$$

$$= \frac{5\cdot38}{6\cdot5}$$

$$= 0\cdot829$$

On the load being increased, the elastic deflection increased until those fibres sustaining the maximum stress were strained beyond their elastic limit, and permanent buckling took place. The maximum load supported by the pillar was 88·7 tons, or 198,000lbs.

Now, using Rankine's formula, and assuming f to be 38,000lbs. per square inch, the values of the other symbols are:—

A = 6·5 square inches,
P = 88·7 tons = 198,000lbs.,
k^2 = 0·829,
l = 5·46ft. = 65·52in.,
f = 38,000lbs. per square inch,

and, taking

$$C = \frac{1}{18000}$$

Rankine's formula says:—

$$P = \frac{f.\,A}{1 + C\frac{l^2}{k^2}}$$

$$= \frac{38,000 \times 6\cdot5}{1 + \frac{1}{18000}\,\frac{4,300}{0\cdot829}}$$

$$= 191,500\text{lbs.}$$

$$= 85\cdot7 \text{ tons}$$

Therefore the buckling load as calculated by Rankine's formula is slightly lower than the actual load.

Next, using Johnson's parabolic formula,

$$P = A\left[34{,}000 - 0{\cdot}67\left(\frac{l}{k}\right)^2\right]$$

$$= 6{\cdot}5\left[34{,}000 - 0{\cdot}67 \, . \, \frac{4{,}300}{0{\cdot}829}\right]$$

$$= 198{,}000\text{lbs.}$$

$$= 88{\cdot}4 \text{ tons.}$$

which is fairly near the actual load.

In Gordon's formula,

$$P = \frac{f . A}{1 + a\left(\frac{l}{d}\right)^2},$$

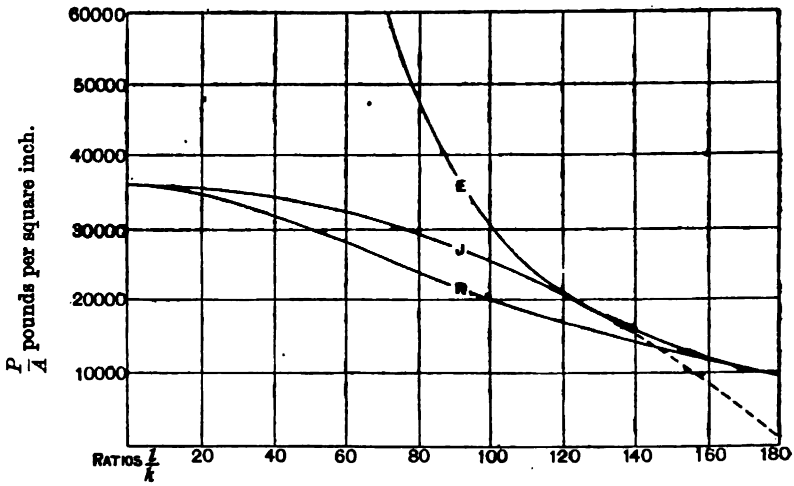


FIG. 152.

CURVES SHOWING THE CRIPPLING STRESS $\frac{P}{A}$ FOR WROUGHT IRON STRUTS HAVING DIFFERENT RATIOS $\frac{l}{k}$ (ROUNDED ENDS).

E Euler's Curve from equation $\frac{P}{A} = \frac{\pi^2 E k^2}{l^2}$

J Johnson's Parabolic Curves from $\frac{P}{A} = 36{,}000 - 1{\cdot}08 \frac{l^2}{k^2}$

R Rankine's Curves from equation $\frac{P}{A} = \frac{36{,}000}{1 - \frac{1}{12{,}000} \frac{l^2}{k^2}}$

taking f as 36,000lbs., and a as $\frac{1}{2250}$ for I pillars,

$$P = \frac{36{,}000 \times 6 \cdot 5}{1 + \frac{1}{2250} \cdot \frac{4{,}300}{16}}$$

$$= 197{,}000\text{lbs.}$$

$$= 92 \text{ tons.}$$

Lastly, trying Euler's formula, where

$$P = \frac{\pi^2 . E . L .}{l^2}$$

$$= \frac{\pi^2 . \ 30{,}000{,}000 . \ 5 \cdot 38}{4{,}300}$$

$$= 326{,}000\text{lbs.}$$

$$= 168 \text{ tons,}$$

a result far too large. For pillars whose ratio $\frac{l}{k}$ is much below 150, Euler's formula is misleading.

CHAPTER X.

GENERAL PHENOMENA EXHIBITED BY TEST PIECES UNDER VARYING CONDITIONS.

154. The strength properties of metals as gathered from the results of mechanical tests can be divided into two classes. Firstly, each specimen exhibits qualities inherent to the material itself, these qualities varying only with the material, and not being dependent upon any outside circumstances connected with the test. In the second place, certain general results may be expected to follow certain methods of treatment of the test piece, either before or during the test. Among such external influences may be mentioned the manner of holding the specimen, the form of the specimen, the influence of temperature both before and during the progress of the test, and of the speed of loading. Some of these general properties will now be described.

155. **Forms of Test Pieces.**—In order to fully appreciate how the results of a test are affected by the shape and proportions of the test piece, consider the case already referred to on page 143. Here is a bar of ductile metal—mild steel—broken in tension in the ordinary way. Previous to the test a number of 1in. lengths were marked off along the bar. After the test these were measured, and all were found to have increased in length, but not all to the same extent. Those inches near the fracture were extended much more than those more remote, owing to the local extension and the greater reduction in the area of cross section at the point of fracture. The percentage extension as reckoned on the full 10 inches is 30·6 per cent.

If, now, the first inch is omitted, and the extension reckoned on the remaining nine (see p. 148), the extension will be:

$$\frac{2{\cdot}87}{9} \times 100 = 31{\cdot}9 \text{ per cent.}$$

Similarly, omitting two, three, and so on, always retaining the point of fracture, the extensions become:

				Extension. Per cent.
Inch No. 1	to inch No.	10,	inclusive	30·6
,, 2	,,	10,	,, ...	31·9
,, 3	,,	10,	,, ...	33·4
,, 4	,,	10,	,, ...	35·1
,, 5	,,	10,	,, ...	37·0
,, 6	,,	10,	,, ...	38·5
,, 7	,,	10,	,, ...	41·2
,, 8	,,	10,	,, ...	45·0
,, 8	,,	9,	,, ...	55·0

From which it will be seen that, for a test bar of a given material and having a given cross section, the extension may vary from 30 to 55 per cent., according to the length of the bar and the length upon which the extension is measured. So that it is not only necessary to report on the percentage extension, but also to mention the measured length. The extension, without the length on which it has been measured, is of little use. It is, unfortunately, not always possible to measure the extension on any desired length, because many specimens, especially these cut out of larger masses of the material, are necessarily restricted in their length. In ordinary commercial testing, extensions are measured on lengths varying from 1in. to 10in. in the more usual cases.

It has been suggested that the measurement of extension should be confined to the parallel part of the bar and not include that part which partakes of the local contraction.

As applied to the case already quoted, the result of doing this would be:

		Extension. Per cent.
Percentage extension on inches Nos.	1..............	19·0
,, ,, ,,	1 and 2	19·5
,, ,, ,,	1, 2, and 3...	20·0
,, ,, ,,	1, 2, 3, and 4	21·0
,, ,, ,,	1, 2, 3, 4, and 5	22·5
,, ,, ,,	1, 2, 3, 4, 5, and 6	23·5
,, ,, ,,	1, 2, 3, 4, 5, 6, and 10	23·7

From these figures it will be seen that the results are much more uniform when the local contraction is left out. This bar was more than usually variable.

Mr. Wicksteed has investigated this point, by making experiments on four sets of bars, three all alike in each set. All the bars were of the same diameter but of different lengths. Mr. Wicksteed, in dividing the local extension from the extension on the parallel portion of the test piece, calls these two respectively, the *strictional* and the *proportional* extensions. The following are the results of the tests.*

Diameter in inches.	Length between Shoulders, inches.	Elongation.			Ultimate Stress in tons per sq. in.
		Total per cent.	Proportional per cent.	Strictional inches.	
$1\frac{1}{8}$	2	50	25·0	0·5	22·90
$1\frac{1}{8}$	$4\frac{1}{4}$	37	25·2	0·5	21·50
$1\frac{1}{8}$	$6\frac{1}{4}$	.33	25·1	0·5	22·03
$1\frac{1}{8}$	$10\frac{1}{4}$	30	25·4	0·5	21·30

From an inspection of these results, it will be clear that the extension measured on the whole length of a bar, of whatever ratio of length to diameter, is very misleading in the case of bars of ductile materials giving local contraction. When the elongation was measured on the total length, the percentage elongation varied from 50 to 30 per cent., being, of course, greatest in the short bars. The proportional or parallel extension, when the local effect has been eliminated, is sensibly uniform for all bars. Apart from the dimensions of the test piece, there must of necessity be small differences in the extension due to want of uniformity of the metal itself.

It would, therefore, appear to be reasonable, for purposes of comparison, when the test pieces are of various sizes and dimensions and proportions, to quote in the report the proportional as well as the general extension of the bar; and, in addition, the percentage of reduction of

* *Industries*, 1890, II., p. 299.

area. The last mentioned is a good and sound criterion of a metal's ductility, and is independent of the length of the specimen.

156. Similar Test Bars.—Another way of getting over the length difficulty would be to adopt a certain fixed ratio of length to diameter for all test pieces. The following test results for a set of bars of various sizes having a constant ratio of length to diameter, and of the same metal, made by M. Barba,* show that for similar specimens of the same material the extensions will be practically constant:—

TESTS OF BARS OF MILD STEEL.

Number of Bar.	Ratio of Length to Diameter.	Reduction of Area Per Cent.	Total Elongation Per Cent.
1	1 to 7·24	69·3	32·8
2		69·0	33·2
3		69·7	33·0
4		68·6	33·5
5		69·2	33·6
6		69·7	33·2
7		68·8	33·0
8		69·5	34·0
Means.		69·2	33·3

These and other tests show that constant results may be expected from similar bars of the same material. Unfortunately, however, it is not possible to take advantage of this, chiefly because it would, in most cases, involve too great an expenditure of time and money in machining the bars to the required proportions. In plates, for instance, it is convenient to adhere to one size and to machine the specimens in batches, and for short specimens, such as those cut from tyres, in order to make them of the proper proportions it would be necessary to make the diameter far too small.

157. Relation between Elongation and Reduction in Area.—It has already been pointed out that, assuming the volume of the bar to remain constant, and so long as it

* Hackney on "Test Pieces," Min. Proc. Inst. C.E., Vol. lxxvi.

retains its parallel shape, the reduction in area *reckoned on the original area* must be equal to the percentage extension *reckoned on the final length* (see p. 40). In the great majority of tensile tests of ductile materials this relation does not hold after the maximum load owing to the local extension, though, if measurements be taken of the bar at a point previous to the maximum load, it will generally be found that the conditions are satisfied.

In the case also of some classes of steel there is little or no local extension and the relation is again found to hold. As an example of this the following, given by Mr. Hadfield in his paper on manganese steel,* may be quoted.

The test results given on the report for one bar were :—

Maximum Stress tons per sq. in.	Percentage Extension measured on 8 inches.	Percentage Reduction in area.
69·33	48·6	32·3

From these results the final length of the specimen can be determined, and from it the extension, calculated on the final length.

The final length of the specimen was

$$8 \text{ inches} + 46{\cdot}8.\frac{8}{100} \text{ inches.}$$
$$= 8 + 3{\cdot}74 = 11{\cdot}74 \text{ inches.}$$

So that

$$\frac{l}{L+l} = \frac{3{\cdot}74}{11{\cdot}74} = 31{\cdot}9 \textit{ per cent.}$$

and,

$$\frac{A-a}{A} = 32{\cdot}3 \textit{ per cent.}$$

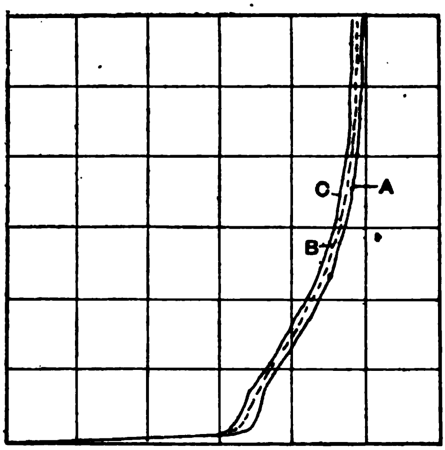
Though these two figures, representing respectively the extension reckoned on the final length and the reduction in area, are not quite identical, they only differ by about one per cent., which is easily accounted for by want of

* Min. Proc. Inst. C.E., Vol. xciii.

uniformity in the material and slight inaccuracies in taking the measurements.

Owing to the fact that the part of the bar which partakes of the local extension assumes a more or less conical form, the reduction in area is necessarily greater than the extension of the locally-extended portion calculated on the final length, and therefore all the more so when taken on the original length.

158. Influence of Time on Plastic Strain.—When a stress beyond the elastic limit is applied to a tension bar, it appears reasonable to suppose that the semi-plastic strain cannot take place at once, because the particles require time to move into their new positions as they follow the flow of the metal. This fact is often apparent in tension tests when it is desired to take measurements of the length of the specimen at stated intervals of load; with a ductile metal a considerable time must be allowed to elapse at the higher loads before the beam of the machine comes sufficiently to rest to allow the extension to be measured. If two similar bars



Loads.

A Loaded at 5·4 tons per square inch per minute.
B " 1·8 " " "
C " 0·66 " " "

FIG. 153.—PROFESSOR BARR'S TESTS ON CHARCOAL IRON WIRE.

are tested, the measurements in one case being taken as soon as the load is applied, and, in the other, a considerable time being allowed to elapse, it will be found

that the extensions for given loads will be less in the former case than in the latter. That this is so is shown by autographic diagrams taken under the two conditions.

On Fig. 153 are shown two load-strain diagrams given by Professor Barr,* the curve marked A being for a piece of charcoal iron wire, with the load applied at 5·4 tons per minute per square inch; that marked B, for a piece of precisely similar wire, loaded at the rate of 1·8 tons per square inch per minute, and C is for the same wire, loaded at 0·66 tons per square inch per minute. It will be seen that there is a considerable difference in the form of the curves.

On the other hand, Col. Maitland† has shown that the *ultimate total* elongation may be increased after extremely rapid loading, such as is effected by the explosion of gunpowder. The explanation of this, given by Unwin, is that the very rapid loading does not allow of the formation of the local "waist" and the general extension continues up to the point of fracture.

Colonel Maitland, in applying his sudden loads to specimens of gun steel, first attached the lower end of the specimen to a dead load which was supported in position. By removing the support, the load was allowed to come upon the specimen suddenly, and the elongation was increased from 27 per cent. with a gradually applied load to 47 per cent.

In order to make the application still more rapid, two closely-fitting plugs or pistons were fitted into a strong accurately-bored cylinder, and the two ends of the specimen to be tested were attached to these. The annular space between the specimen and the cylinders was filled with guncotton or gunpowder and exploded. The effect of this was to give an elongation of from 47 to 62 per cent. In some cases the specimen fractured in two places, leaving a cigar-shaped piece between.

These results appear to show that a rapidly-applied load in a testing machine gives a smaller elongation than when the load is very gradually applied, owing to the shorter time allowed for the metal to flow into its position of equilibrium; but that, when the suddenness of application is greatly increased, the conditions are again altered, there being little time for the local effects,

* Min. Proc. Inst. C.E., Vol. lxxxviii.
† Min. Proc. Inst. C.E., Vol. lxxxix.

and the general, and with it the total, elongation being again increased.

The effect of time influence on the strain of compression specimens is shown on the diagram on Fig. 154. The curves here shown represent the relation of stress and strain for two specimens of soft copper tested by the author. The two specimens were turned from the same bar, and were of the same size, being about 1in. in diameter and 1½in. in length.

In the case of the first one, after each increment had been applied, the specimen was allowed ample time to come to

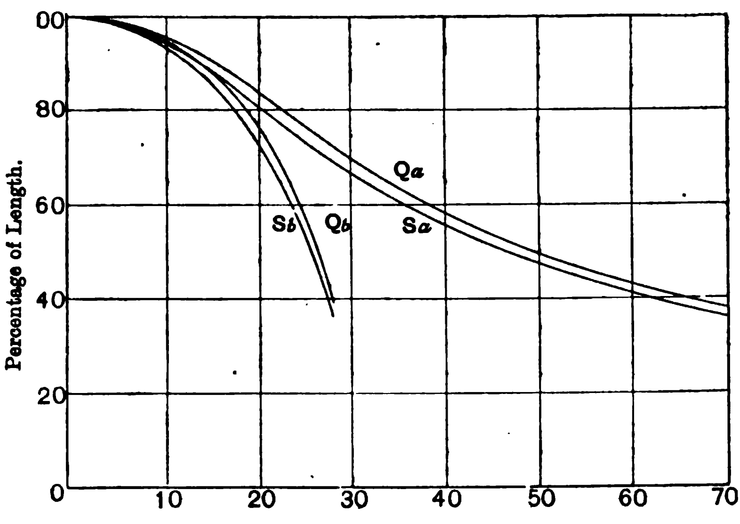


FIG. 154.—THE AUTHOR'S TESTS OF TWO COPPER COMPRESSION SPECIMENS.

rest and take up its full amount of set, for the larger loads this time in some cases amounted to 20 minutes. When this had been done, and before a new load was applied, the bar was taken out of the machine and both its length and diameter at the two ends measured. From these measurements it was possible to calculate the actual stress on the specimen at each length.

For the second bar the operations were precisely the same, except so far as regards the time during which the load was allowed to remain on the specimen. It is impossible to apply the load in a testing machine with

absolute suddenness, but in the present instance the load was put upon it as quickly as possible and at once removed, and the measurements taken as before.

The curves show very well the difference exhibited. The curve marked S_a is the load-strain curve for the slow loading, and that marked Q_a is the corresponding curve for the rapid loading. S_b and Q_b are the curves showing the actual calculated stresses and strains for the same two bars.

The two latter curves show the line becoming nearly vertical towards the end of the test, indicating an almost plastic condition, as indicated by the stress on the metal being more and more nearly constant.

The slowness in taking permanent set becomes of great importance when the amount of set is used as a

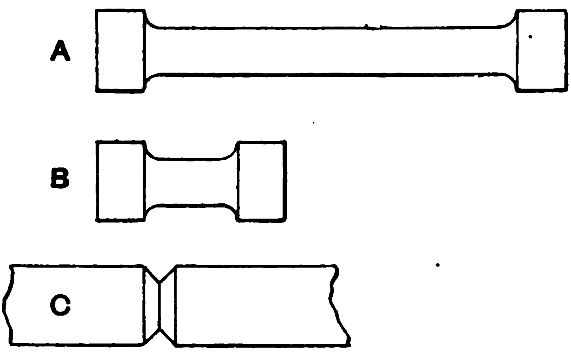


FIG. 155.

measure of the compressive load, as is the case in the copper crusher gauges used for determining the explosive pressures in the bores of guns. Here the copper cylinders are compressed by the pressure of the gases, and exactly similar cylinders are compressed to the same extent by measurable loads, and the compressive force in this way found. It is obviously important that the test loads shall be applied at a rate not very dissimilar from those due to the gas pressures.

159. Influence of the Forms of Ends on Strength and Deformation.—On Fig. 155 three forms of tension specimens are shown; of these A is a parallel turned bar with cheese heads, the length between the shoulders being, say, 12in; C is of the same material and diameter, but having practically no length, the reduction in diameter

from the head being simply made by cutting a nick in the bar; B has proportions intermediate between A and C. The results of tests made on these three bars have been shown by experiment to be very dissimilar.

In A and B the gauge marks are 1in. distant from the shoulders. The bar A will probably give the normal results to be expected from a bar having no heads and turned parallel, both as regards strength and ductility. In the case of C the maximum strength will be very much higher than that given by A, and the elongation and reduction will be practically nil. The third bar, B, may be expected to give results intermediate between the others; the maximum strength will probably be greater, but not very markedly so, than that of A; the total elongation will be greater and the reduction in area less.

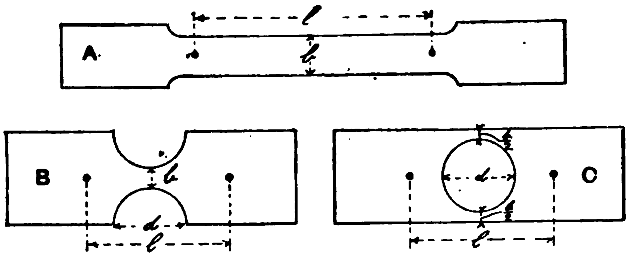


FIG. 156.—STROMEYER'S TESTS.

These results, which experiment has shown to be generally true for ductile metals, are due, in the first place, to the influence of the larger unstrained heads, in retarding the natural flow of the metal during the period of drawing out. In the shorter bars. the normal elongation and reduction are interfered with. The greater elongation in the case of the shorter bars is due to the cause which has been already mentioned, namely, the larger proportion which the local elongation forms of the whole.

Professor Unwin* quotes two experiments illustrating these facts. Two bars were tested, similar in form to those at B and C (Fig. 155), the longer specimen having its larger diameter 2$\frac{1}{4}$in. and the diameter of the part tested 1$\frac{1}{2}$in. by 2$\frac{1}{4}$in. long; the other specimen was nicked as at C, the diameters being respectively 1$\frac{1}{2}$in. and 2$\frac{1}{4}$in. as in

* Unwin's "Testing," page 82.

the case of the first bar. The tests showed the breaking strength of the parallel specimen to be 35·87 tons per square inch, and for the nicked specimen 53·25 tons per square inch. These results show very well the effect of the suppressing of the drawing out in increasing the tensile stress.

In the discussion on Mr. Hackney's* paper, Mr. Stromeyer gives the results of some tests he made on test pieces of the forms shown on Fig. 156. Of these there was one made of the form A, four of B, with varying ratios of *b* to *d*, and there were eight bars marked C, also with varying ratios of *b* to *d*. The following table contains the chief results obtained, the measurements being reduced to British units :—

Number of Bar.	Ratio. $\frac{b}{d}$	Elongation of hole. Per Cent.	Total Elongation. Per Cent.	Maximum Stress. Tons per Sq. In.
A			25·5	27·9
B 1	1·94	50	26	30·1
2	1·32	40	18	34·5
3	0·75	27½	14	32·2
4	0·52	21	12	34·5
C 1	2·25	54	28	29·6
2	1·83	50	26	29·8
3	1·42	46	22	29·0
4	1·18	41½	22	28·6
5	0·97	37½	20	31·0
6	0·77	33½	16	28·7
7	0·54	25	14	28·9
8	0·32	21	10	28·6

160. Cracks in the Edges of Bars.—Experiments in this direction have been made by Mr. (now Sir) Benjamin Baker, and the results are given in the discussion on Mr. Stromeyer's paper read before the Institution of Civil Engineers.†

The forms of the bars tested are shown on Fig. 157. Of these A is an ordinary flat test bar of the original

* Min. Proc. Inst. C.E., vol. lxxvi.
† Min. Proc. Inst. C.E., vol. lxxxiv.

material, which was mild steel. All the others were of the same material. In the bar B two small saw-cuts were made, the bar was got to almost a welding heat, and the nicks closed up, so that they were to all intents and purposes hidden cracks in the material. Under the test the strength of the remaining material was not so much reduced as might have been supposed. Two bars of the form C were tested, one held in the ordinary way, and the other held in the machine by pins, both bars being nicked on one side only. The test in this case showed a considerable reduction on the original strength

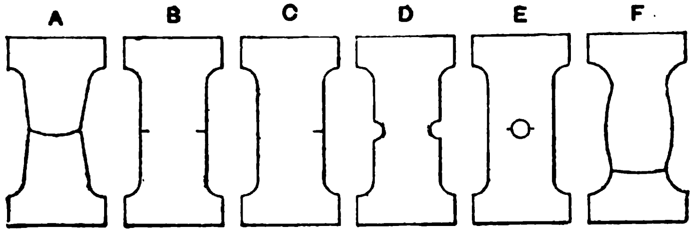


FIG. 157.—BAKER'S TESTS. EXPERIMENTAL BARS.

of the steel, the bar held by the pin giving the lower results. D and E are similar to Mr. Stromeyer's bars already referred to (Fig. 156), except that in E two saw-cuts were made in the side of the hole. The bar marked F was first bent several times at a blue heat and afterwards tested.

The breaking stresses for these bars are given in the following table:—

Bar.	Condition of Bar.	Breaking Stress. Tons per square inch.
A	Original	32·5
B	Saw cut on both sides	31·4
C	Saw cut on one side	24·7
D	Semicircular cuts on outsides ...	36·3
E	Hole drilled and saw cuts	28·0
F	Bar bent at a blue heat	34·4

Referring to the experiments of Mr. Strohmeyer and Sir Benjamin Baker, three conclusions of importance, as regards the proportioning of test pieces and the interpretation of test results, may be drawn. These are :—

Firstly. When the effective length of the specimen is diminished, as in B and C (Fig. 156) and in D (Fig. 157), the strength per square inch of the metal is increased

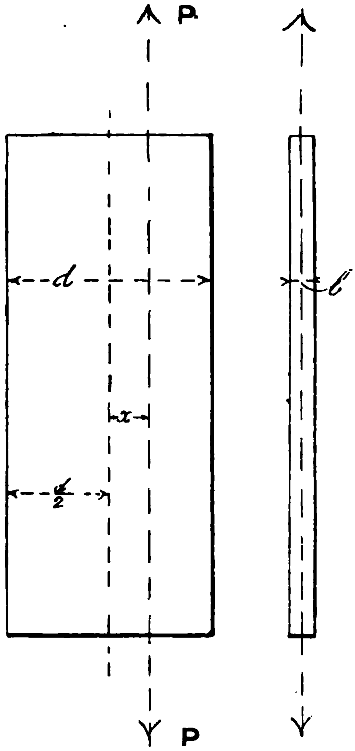


FIG. 158.—UNSYMMETRICALLY LOADED BAR.

beyond that of the original metal to a greater or less extent, according to the proportions of the indentations. This increase is due to the localisation of the extension and the suppression of the drawing out caused by the retardation of the flow of the metal towards the neighbourhood of the fracture.

Secondly. When this shortening of the specimen by indentation is carried to excess, an inequality of the stress in the metal close to the nicks results in the actual breaking stress being lowered.

Thirdly. If the nicking is unsymmetrical, the line of action of the load no longer passes through the centre of gravity of the section, and a tensile stress due to the bending action is added to the original tensile stress, and the bar breaks under a smaller load per square inch of section than does the original bar.

161. Unsymmetrical Loading.—The problem involved in the last case is briefly as follows: In Fig. 158 is represented a bar of thickness b; of width, d; under a tensile load, P, acting at a distance, x, from the centre line of the bar.

This loading will be productive of a stress on a cross section of the bar, which will be variable, and will consist of two distinct parts.

In the first place, there will be a uniform tensile stress, f_t, where $f_t = \frac{P}{b\,d}$, $b\,d$ representing the sectional area of the bar.

Besides this stress, there will be another caused by the bending action of the force as it is applied, not along the axis of the bar, but at a distance, x, from it, thus causing a bending moment on the bar, which in magnitude is equal to P x.

The stress due to this bending action is

$$f_b = \frac{6\,P\,x}{b\,d^2}$$

The total or resultant tensile stress is the sum of these two, or

$$\begin{aligned} f &= f_t + f_b \\ &= \frac{P}{b\,d} + \frac{6\,x\,P}{b\,d^2} \end{aligned}$$

The more general expression is

$$\begin{aligned} f &= \frac{P}{A} + \frac{x\,P}{Z} \\ &= \frac{P}{A} + \frac{y\,x\,P}{A\,k^2} \\ &= \frac{P}{A}\left(1 + \frac{y\,x}{k^2}\right) \end{aligned}$$

where y is half the depth of the section ; and k is the "radius of gyration," whose value is

$$k^2 = \frac{I}{A}$$

In the case of the bar which has already been referred to (C, Fig. 157), a nick is cut in one side of the bar, thus throwing the remaining section out of centre, the line of the load passing now to the right of the centre of the section, so that, in addition to the bar being weakened by the nicking itself, it is further weakened by the load being out of the centre of the section upon which the load is brought to bear.

This question of loading a tension bar out of the centre is fully discussed in the Proc. Inst. Civil Engineers, vol. cxxxiv., by Professor W. E. Dalby.

162. General Deductions.—A few general principles may be deduced from what has just been said as to the influences which affect the results of tests, quite apart from the inherent properties of the material tested.

Perhaps the most important of these is in regard to the form of the specimen itself. The bar should be fairly long, if possible eight or ten times the diameter, so as by this means to get a reliable extension. In some cases, of course, this is impossible, and one has to be content with a very short specimen. If there are heads at the ends of the bar, the parallel portion upon which the measurements are taken should merge into the heads by gradual and easy curves, and there should be no sharp corners. Also, where possible, the marks denoting the ends of the measured portion should be well clear of the heads, so that the extension may not be affected by them.

Unsymmetrical loading, caused by a faulty form of the ends, should, of course, be avoided, and it is also obvious that there should be no cracks or grooves on the surface of the specimen. The extensions will not be greatly affected by the speed of loading under the ordinary conditions obtaining in most testing machines, but the effect of very gradual and very sudden loading in extreme cases, both as regards strength and deformation, should be borne in mind.

163. The Elastic Limit in Tension.—Some ambiguity exists as to the correct meaning of this term. The words "elastic limit" are used to describe several things which are not quite the same, and some confusion has in consequence arisen.

In its original and true meaning, the elastic limit of a material is that stress beyond which the strain will not wholly disappear on the removal of the stress. In other words, when the stress imposed produces the smallest possible amount of permanent set, the material can no longer be regarded as truly elastic, and the limit has been passed.

This is a rather more rigid definition than saying, as it is often done, that the elastic limit is the stress beyond which the strains cease to be proportional to the stresses. By this latter definition, if a stress-strain curve is plotted, and the straight portion produced, the point where the curve departs from the tangent is taken as the true elastic limit. But the accurate determination of this point is dependent, to a great extent, on the degree of precision of the instrument with which the extensions are measured. An extensometer reading accurately to ten-thousandths of an inch will detect the limit sooner than one only reading to thousandths.

The first definition given above is that of the true, or what is often called the scientific elastic limit. This is to distinguish it from the more commonly used or commercial elastic limit, which is a point in the loading a little beyond the true limit, where a very large increase takes place in the strain, with little or no increase in the stress, producing a distinct "jump" or step in the plotted curve. This point has also been called the "yield point" and the "breaking down point," to signify the apparent sudden breaking away or yielding of the substance. As previously stated, the commercial limit or yield point is roughly determinable by noting the sudden drop of the testing machine lever when it occurs, or better, by placing a pair of dividers on a marked length of the bar, and noting when one point leaves its mark.

These two limits are the ones commonly made use of, namely, the *Scientific* or *True Elastic Limit* and the

Commercial Limit, perhaps better called the *Yield Point* in order to prevent ambiguity. In the report of the French Commission on Testing, three limits are defined as follow :—

Elastic Limit is the unit stress beyond which a portion of the deformation remains as permanent set.

The Proportional Elastic Limit is the point where the deformation ceases to be proportional to the load.

The Apparent Elastic Limit is the point where the deformations increase rapidly without any increase in the force exerted.

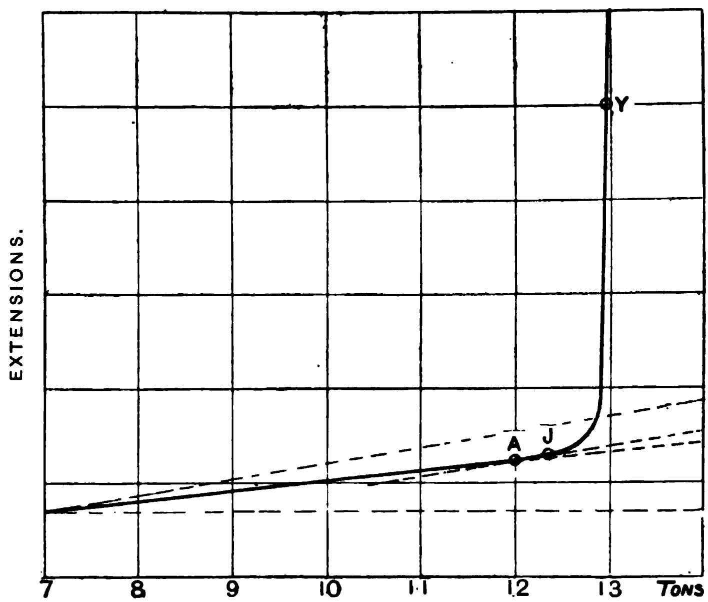


FIG. 159.—LOAD-STRAIN CURVE FOR MILD STEEL, SHOWING ELASTIC LIMITS.

In order to render the useful elastic limit more definite, Professor Johnson has thus defined it :—

The Apparent Elastic Limit is the point on the stress diagram of any material, in any kind of test, at which the rate of deformation is 50 per cent. greater than it is at the origin. This point is determined by first finding a line whose inclination has a tangent half as great again

as the tangent of the early part of the diagram, and then finding where a line of this inclination just touches the strain diagram. This point will be the *Apparent Elastic Limit.*

On Fig. 159 are plotted the strains for a test given. Here Y is the yield point or commercial limit; J is the apparent elastic limit obtained according to Johnson's rule; A is the proportional elastic limit of the French Commission; while the true elastic limit, which was not determined in this case, will be slightly nearer the origin.

So far as commercial testing is concerned, the only elastic limit which is recognised and taken account of is the yield point. It is near the true limit, and can be determined with far greater ease and certainty without

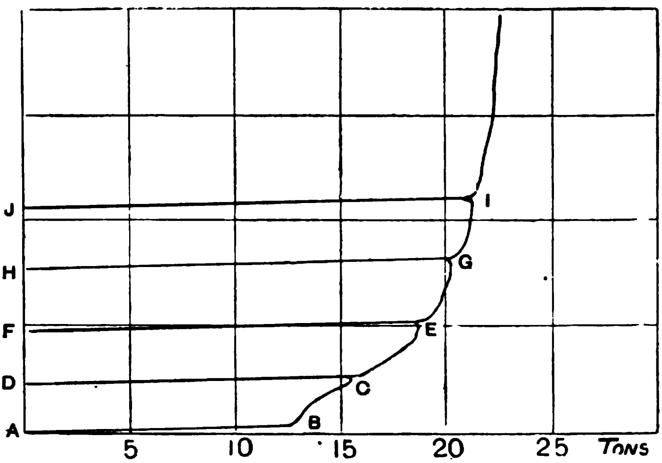


FIG. 160.—DIAGRAM SHOWING THE RAISING OF THE ELASTIC LIMIT.

the employment of instruments of precision, and is sufficiently accurate for all practical purposes.

164. Raising the Elastic Limit by Stress.—It is well known that the result of overstrain on a test bar is to change the load at which the elastic limit occurs, and any further repetition of this overstraining will produce a new limit. The meaning of this will be clear from a consideration of the diagram on Fig. 160.

The origin of the load strain curve is at A. As the test proceeds, the diagram follows the straight line up to B, where the yield point occurs. From this point the curve follows the usual upward semiplastic curvature towards C. If, now, at C, some point above the yield point, the load is removed, an elastic contraction will take place, and this is shown, either by an autographic apparatus or by taking observations with an extensometer and plotting, by the straight line C D parallel to A B.

On the load being again increased, beginning from D, the extensions will be such that the curve will be retraced along D C; when C is again reached, the point C being found to be the yield point for this second loading, the semiplastic extension will take place in the direction C E.

And so on for any further loadings, a new limit being established for each successive stage. It would appear as if, after each overstrain, a new metal was produced, having a higher yield point than before exposure to the stress above its former limit. The curve A B C E G I, and so on, would coincide approximately with the complete load-strain curve drawn for the original bar without any unloading having taken place.

Owing to the fact that all the elastic portions of the curves A B, C E, D C, F E, H G, I J, &c., are found to be parallel, it is to be assumed that the modulus of elasticity in each case is sensibly the same for the same bar.

In order to prevent any mistakes as to these successive limits, the first limit, as it is found for the unstrained material, has been termed the *primitive* or *original elastic limit.*

Both the modulus of elasticity and the elastic limit are affected by the temperature to which the bar is exposed. The modulus in all metals decreases to a small extent with a rise in temperature. Thus, if wrought iron or steel is raised in temperature from 60° Fah. to 360° Fah., it will be found that the modulus has been reduced about six per cent. This value is quoted by Johnson* as deduced from published results of tests at the Wartertown Arsenal.

The elastic limit for steel also decreases continuously as the temperature increases, a rise in temperature of

* Johnson's "Materials of Construction," page 562.

300° resulting in a fall in the limit load of some 6 per cent.

165. Effect of Annealing.—The effect of annealing on an overstrained steel bar is to bring the metal back to its original state. This is shown very forcibly by the results of some endurance tests made on two steel bars by Mr. Coker. In these tests, the bar was taken and loaded to just beyond the yield point, the permanent set being a quarter of an inch. The bar was then annealed by heating to a dull red heat and cooling slowly in lime. After this, the bar was again loaded until the extension was a quarter of an inch. This process was repeated 37 times in the case of one bar and 39 times in the case of the other. It was found that the yield point, instead of being continually raised, as would be the case without annealing, was approximately constant throughout the whole series, fluctuating about a value of 17 tons, and generally keeping between 15 and 19 tons per square inch. It was also found that the total extension of the bar was about four times what it was for a bar of the same material tested in the usual way.*

166. Effect of Annealing on Wire.—Cold-rolling and wire-drawing give rise to effects which are analogous to the overstraining of a test bar. The elastic limit is raised, and also the breaking strength, while the ductility, as shown by the extension and reduction in area, is reduced.

These points are shown very well by the results of Mr. Keigwin's† tests on unannealed and annealed steel wire. Here the strength of the wire when annealed was found to be lowered to that of the billet from which it was drawn, or a reduction of 39 per cent.; the ratio of yield point to breaking was lowered by annealing; while the elongation and reduction in area were greatly increased.

Another effect of loading a ductile material by exposing it to a steady load not far removed from the breaking load for a considerable period of time, shown by Lord Kelvin, is an increase of strength and loss of ductility. It was found that the effect of this long-imposed stress was to cause the specimens to break at a much higher load than the original unstrained bars.

* Min. Proc. Inst. C.E., vol. cxxxv.
† Min. Proc. Inst. C.E., vol. cxxxvi.

The effects of previous loading on test bars may, therefore, be summed up as follows :—

(*a*) If the bar is strained beyond the yield point, and the load removed, a second loading will be accompanied by a higher yield point than before, and similarly for every repetition.

(*b*) In the case of steel, if the bar is annealed after the overstraining, the yield point will be approximately the same as in the original state.

(*c*) Cold rolling and wire drawing, without annealing, raise the yield point, increase the ultimate strength, and lower the ductility.

(*d*) Annealing restores the metal approximately to its original state.

(*e*) The effect of a long-continued load beyond the yield point is to increase the ultimate strength and diminish the ductility.

CHAPTER XI.

EXPERIMENTS ON THE RELATION OF STRESS AND PERMANENT STRAIN; AND REPEATED STRESSES.

167. Relation between Stress and Permanent Strain. Just as in elastic deformation there is a definite relation existing between the applied stress and the strain produced, so a law can be found for any given plastic material, which formulates the relation existing between a stress and its permanent strain. By making a series of careful experiments on bars in a testing machine, noting the stresses and corresponding strains, and plotting the

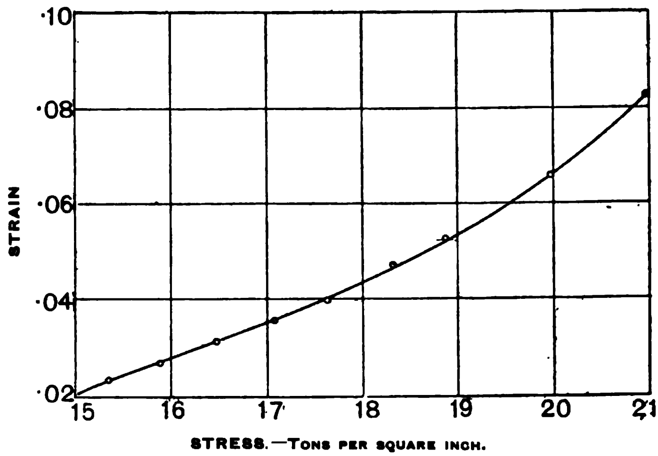


FIG. 161.—STRESS-STRAIN DIAGRAM FOR WROUGHT-IRON BARS.

stress-strain curve in the usual way, a graphic representation is obtained of the relation required in the form of a curve, and an equation can be found to fit this curve.

The method of obtaining the equation will be made clear from a consideration of the following description of a series of interesting experiments made by Dr. T. E. Stanton,* now of University College, Bristol, with the object of determining a definite relation between the

* Mem. and Proc. Manchester Lit. and Phil. Soc., 1893-4.

uniform tensile stress and the corresponding semiplastic strain in the case of wrought iron and steel.

The first series of experiments were made upon nine bars of wrought iron of soft quality, each bar being

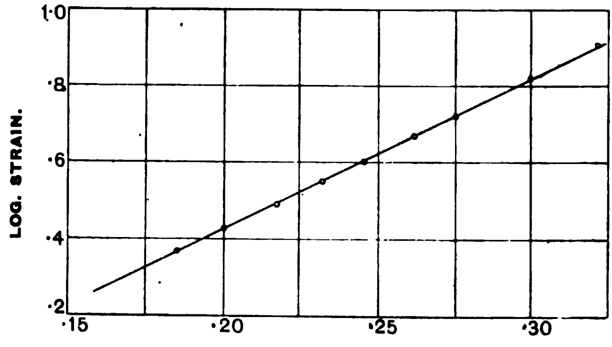


FIG. 162.—LOGARITHMIC DIAGRAM OF STRESS AND STRAIN.

turned parallel. In order to avoid the effect of previous loading on the extension, each bar of the set was subjected to one load only, the load being allowed to remain on the bar for 30 minutes before the extension was measured. The nine pieces tested were cut from one bar, which made it possible to combine the results in the form of a single stress-strain diagram for the range of load employed. This is shown in Fig. 161.

Using Prof. Osborne Reynolds' method of logarithmic plotting, it was found that by plotting the logarithms of the strains, expressed as fractions of the original lengths, as ordinates, and the logarithms of the corresponding real stresses as abscissæ, the line shown on Fig. 162 was obtained. It will be seen that the points corresponding to the various bars and loads all lie on a straight line, whose equation has the general form

$$\log. f = \log. C + k \log. e$$

where f is the real stress on the bar,

,, e is the corresponding strain, which in this case is an extension, and is equal to $\frac{L - l}{l}$;

and C and k are constants depending upon the material tested.

Taking the logarithms of both sides of the above equation, the standard equation is obtained, having the form

$$f = C\, e^{k}$$

For the nine bars tested, the slope of the curve gave the value of k as 0·25, and the mean value of C as 39·4.

Further tests, both on sets of bars as above and on single bars, gave the following results :—

Set of 9 bars of brand R.H., Crown B.B.B.	0·25	39·40
Single bar ,, ,,	0·25	40·30
Single bar ,, ,,	0·25	40·35
Set of 9 bars brand R.H., Crown B.B.	0·265	39·30
Single bar ,, ,,	0·275	40·416
Single bar ,, ,,	0·265	39·252
Single specimen cut from a bar of mild steel	0·25	50·160

The actual figures obtained for the first set of bars are the following :—

No. of Speci-men.	Initial Area. Square Inch.	Final Area. Square Inch.	Permanent Strain.	Stress on Reduced Section. Tons.	Value of C.
Z1	0·7643	0·7420	0·03071	16·480	39·37
Z2	0·7590	0·7238	0·05227	18·873	39·48
Z3	0·7528	0·6999	0·08133	20·977	39·32
Z4	0·7648	0·7378	0·03978	17·620	39·46
Z5	0·7605	0·7158	0·06585	19·973	39·42
Z6	0·7810	0·7638	0·02330	15·338	39·27
Z7	0·7600	0·7412	0·02689	15·893	39·25
Z8	0·7510	0·7178	0·04668	18·306	39·38
Z9	0·7560	0·7306	0·03490	17·068	39·49

Proceeding on similar lines, Dr. G. Wilson,† has made corresponding determinations for annealed copper bars in tension. The values of the constants obtained in the equation

$$f = C\, e^{k}$$

are as follow :—

† Mem. and Proc. Manchester Lit. and Phil. Soc., 1898-9.

TEST.	k.	C.
1	0·535	38·08
3	0·535	38·97
4	0·503	36·16
5	0·526	37·86
6	0·519	37·47
Means.	0·524	37·91

The author has found that a precisely similar relation exists in the case of permanent compressive strains, as for tension, by testing copper compression cylinders and plotting the logarithms of the strain and stress. The mean results obtained were:—

k.	C.
0·488	39·00

Similarly, testing a short piece of Lowmoor iron in compression, the author finds the following values to be given:—

k.	C.
0·240	43·700

Which agree fairly well with the figures obtained from tension tests.

REPEATED STRESSES.

168. A very large proportion of engineering structures and parts of machines are exposed to stresses which may be regarded as unvarying in both their magnitude and their direction; that is to say, they are subjected to steady loads, and, so long as these loads are so chosen as not to strain the material beyond the elastic limit, they will have no deteriorating effects, no matter how long they are allowed to remain on the material. In other words, time, so far as we are able to tell, has no material effect on the condition of a substance subjected to steady loads within the elastic limit.

Other parts of structures, again, are exposed to stresses which are constantly being taken on and off, such as in the tie-bars of bridges and pillars whose loads are intermittent. In these, so long as the imposed loads do not give rise to stresses which are at any time beyond the elastic limit of the material, the time during which these structures will safely withstand their loads is practically unlimited.

The same is true of a third class of structures which are subjected not only to repeated loads, but, at the same time, to loads which are constantly being reversed in direction. An example of such a case is to be found in an ordinary clock spring, which has to withstand many millions of reversals of stress every year, and yet is to all intents and purposes unaffected after the lapse of many years. Here is an almost perfectly elastic material in which the stresses never approach a limit of the elasticity.

As, however, the stresses become greater in magnitude, and, in the case of reversed stresses, the range of stress increases, the number of repetitions or the number of reversals required to produce failure diminishes. For instance, it has been shown that a bar of Krupp axle steel, subjected to a repeated stress of 15·29 tons per square inch, requires 274,970 repetitions of the stress to cause failure, whereas, under a stress of 23·89 tons per square inch, 23,546 repetitions will be sufficient to fracture the bar.

169. Wöhler's and Spandenberg's Experiments.—By far the most important and exhaustive researches into this subject were made for the Prussian Government, by Herr Wöhler, between 1859 and 1871, and afterwards continued with the same apparatus by Prof. Spandenberg, his successor.

Four series of experiments were carried out as follow:—

(*a*) **Repeated Stresses in Torsion.**—For this purpose a cylindrical bar with enlarged ends was employed. One of its ends was held in a gripping device controlled by springs, and the other was attached to one end of a rocking lever, which was driven by mechanical power, and whose angular movement was controlled so as to keep it within certain limits. In this way the maximum

stress on the material was limited to a certain prearranged magnitude. Loadings, giving rise to both stresses in one direction only and to reversed stresses, were applied.

(*b*) **Repeated Tensions.**—A power-driven machine was used for these tests also, the free end of the specimens being attached to the short end of a rocking lever, whose movement was controlled by springs, so that the stresses could not exceed a certain given amount.

(*c*) **Repeated Bendings.**—A third machine was used for the purpose of imposing a succession of bending stresses on a beam specimen, a stop being provided, so that, in some of the tests, the stress could not be wholly taken off the bar, but kept within previously defined limits.

(*d*) **Reversed Bending Stresses.**—The fourth machine was arranged to apply reversed stresses to cylindrical beams. This was effected by slowly rotating the bar to be tested, one end being attached to the shaft of the machine and the other being free and carrying a load at its outer end, so that, as it was turned through one revolution, it became a cantilever, bent first in one direction and then in the other.

A large number of materials were tested under the various conditions indicated. In all cases the original statical strength of the material was determined in the usual way.

In the torsion tests, some of the bars were tested under stresses in one direction only, the maximum stress attained and the number of repetitions of this stress required to produce fracture being noted. In the others, where the stress was in two directions alternately, the maximum and minimum, and, therefore, the range of stress was found, along with the number of repetitions.

In most of the tension tests the stresses were between zero and a maximum stress; but in some cases the range of stress was between a minimum and a maximum stress. The same is true for the transverse stresses, many of the tests being made with the specimen pressing against a stop on the removal of the load, so that the stress was never entirely removed.

In the tests of the rotating cantilevers, loaded at the ends, the range of stress was necessarily between a

tensile stress on one side and an equal compressive stress on the other.

The general conclusion arrived at from the results of these tests was that the fracturing of the bars depended, in the first place, on the range of stress; and, secondly, on the number of times the stresses were repeated. When a certain minimum stress was reached, it was found that the number of repetitions required to produce fracture was practically infinite.

The following figures, taken from Wöhler's results, will serve to give an idea of the kind obtained. They comprise the results of tests of eight bars of Krupp cast steel for axles, under repeated bending stresses by rotation.

Wöhler's Tests on Repeated Stresses in Bending by Means of Rotation.—

Stress in Tons per Square Inch.		Range of Stress. Tons per Square Inch.	Number of Repetitions before Fracture.
Maximum.	Minimum.		
+ 20·1	− 20·1	40·2	55,100
+ 17·2	− 17·2	34·4	127,775
+ 16·3	− 16·3	32·6	797,525
+ 15·3	− 15·3	30·6	642,675
+ 15·3	− 15·3	30·6	1,665,580
+ 15·3	− 15·3	30·6	3,114,160
+ 14·3	− 14·3	28·6	4,163,375
+ 14·3	− 14·3	28·6	45,050,640

Wöhler himself summarised the results of all his tests in the following law:—

Wöhler's Law: *Rupture of material may be caused by repeated vibrations, none of which attains the absolute breaking limit. The differences of the limiting strains are sufficient for the rupture of the material.*

As a further result of his tests, Wöhler gave the following values for the stresses on steel and wrought iron, which may be imposed for an unlimited number of repetitions without any damage being sustained by the material:—

Wöhler's Limiting Stresses on Wrought Iron and Steel.

Material.	Stress in Tons per Sq. Inch.
Wrought iron, in tension only	+ 8·35 to + 0·013
Wrought iron, tension and compression	+ 2·82 to – 2·82
Cast steel, tension only	+ 15·30 to + 5·10
Cast steel, tension and compression...	+ 5·58 to – 5·58

In this table the plus sign means tension and the minus sign compression. These results show that only in the case of a structure or parts of a structure under a dead load does the safe stress depend on the ultimate strength of the material divided by a standard "factor of safety," and that, where the structure is subjected to repeated and variable loads, the safe stress allowed must be chosen with due consideration of the number of repetitions of the stresses as well as of the complete range of stress imposed.

Besides those of Wöhler, other experiments have been made in the same direction, notably by Bauschinger and Sir B. Baker. For use in designing parts of structures subjected to repeated stresses, several formulas have been devised embodying the results of these endurance tests. Especially to be noted are those of Launhardt and Weyrauch.

CHAPTER XII.

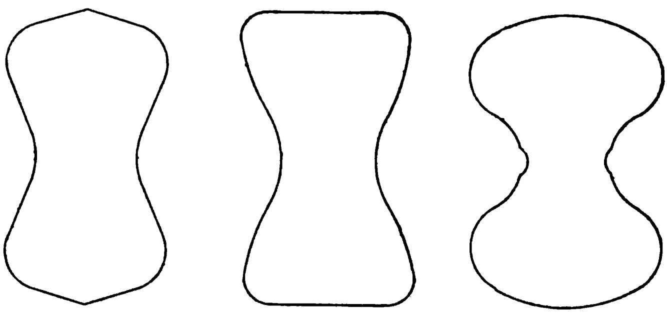
THE TESTING OF VITREOUS MATERIALS AND TIMBER.

PORTLAND CEMENT.

170. Portland cement is by far the most important of the cementing materials used in construction, and of which the strength properties require to be determined by means of systematic tests.

Portland cement may be described as a product, consisting for the most part of aluminates and silicates of calcium, resulting from the calcination of materials containing clay and lime. The process by which it is produced may be summed up as follows :—

(*a*) Material containing clay in some form is intimately mixed with other material containing lime as in chalk.



British and American. Continental.

FIG. 163.—STANDARD FORMS OF BRIQUETTES.

(*b*) The mixture so made, after being dried, is burnt or calcined, during which calcination a chemical change takes place, the silica and the alumina combining with the lime to form the necessary silicates and aluminates.

(*c*) The fine grinding of the resulting product to form a cement which sets hard when mixed with water.

The clayey mud and the chalk used must be mixed in such proportions that the resulting cement contains no excess either of clay or lime. Too much lime, or incomplete mixture of the lime and clay, yields a cement which may show great strength soon after setting, but becomes much weaker afterwards owing to the working or swelling of the excess lime.

Too much clay generally produces a weak, quick-setting cement, which may have a brownish, or "foxey," colour.

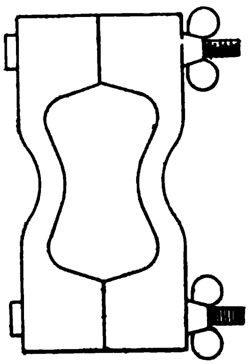


FIG. 163A.—MOULD FOR CEMENT BRIQUETTES.

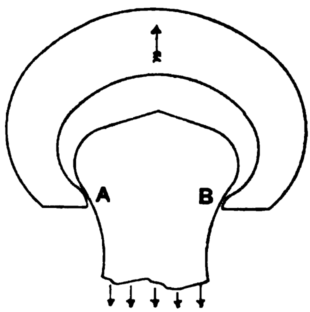


FIG. 163B.—HOLDER FOR CEMENT BRIQUETTES.

* Butler gives the following composition of Portland cement:—

Lime ...	...	...	60 to 64 per cent.
Silica ...	...	...	20 to 24 ,,
Alumina	...	...	6 to 10 ,,
Iron oxide	...	...	3 to 5 ,,

Portland cement weighs from 110lbs. to 124lbs. per bushel. It should be kept in a dry place which is at the same time cool, and should, if possible, be taken out of the sacks or barrels and allowed to remain for some little time, before being used, exposed to the air until any tendency to heating has left it.

* B. Butler, "Portland Cement."

171. Sampling.—When a test or series of tests are to be made on a particular delivery of cement, care should be taken that the sample from which the test pieces are prepared is a representative one. If the quantity is large, samples should be taken from each or several of the sacks or barrels, the sample being taken from well down in the sack or barrel and not from the top. All these samples are to be mixed together and the test specimens prepared from a portion of the mixture. By doing this a fairly representative sample should be obtained.

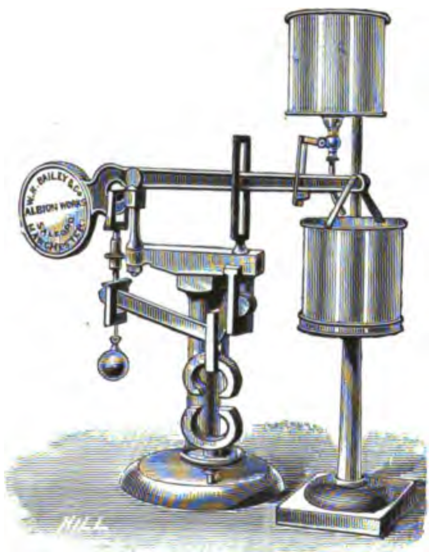


FIG. 164.—BAILEY'S AUTOMATIC TENSION TESTING MACHINE FOR CEMENT.

In specifications for works in which Portland cement is to be used it is usual to state that the cement must satisfy certain requirements laid down in the specification. It is with the intention of seeing whether the cement supplied by the maker does satisfy the specified requirements that the following tests are undertaken. In this country there is no attempt to make the requirements absolutely uniform, each engineer having his own ideas as to the necessary qualities. In other countries, notably

France and Germany, the case is different, certain standard rules being adhered to.

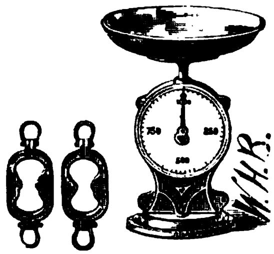


FIG. 165.—WEIGHING SCALE AND CEMENT MOULDS.

Speaking generally, the tests to which a sample of Portland cement is subjected, are as follow :—

Tests for

(*a*) Fineness.
(*b*) Tensile strength.
(*c*) Crushing strength.
(*d*) Soundness.
(*e*) Setting properties.

In addition to these are also

(*f*) Specific gravity, and
(*g*) Chemical composition.

These various tests will now be described in detail.

172. Fineness.—The tendency is to grind cements much finer at the present day than formerly, owing to the fact that the finer a cement is the more thoroughly does it unite with the water with which it is mixed, and the more uniform is the composition. If a cement has been underburned, that is to say, although it contains the requisite amount of lime to satisfy the chemical conditions necessary for proper combination, parts of it may not have been burned to such a point as to have effected complete chemical combination—that is, small portions of lime may exist in the cement *as lime*—and these, often isolated, portions of lime swell on admixture with water, and so cause the cement to crack or "blow." Fine

grinding lessens the deleterious effects of any under-burning that may have occurred, owing to a more complete distribution of any stray portions of unburnt lime throughout the cement. The actual test for fineness is to pass a sample of the cement through a standard sieve of fine brass wire and weigh the residue which is prevented by the sieve from passing through, and to express the fineness as a percentage of this residue. For instance, a pound of the cement may be taken and put through the sieve and the residue found to weigh 0·15lb. In this case the residue would amount to

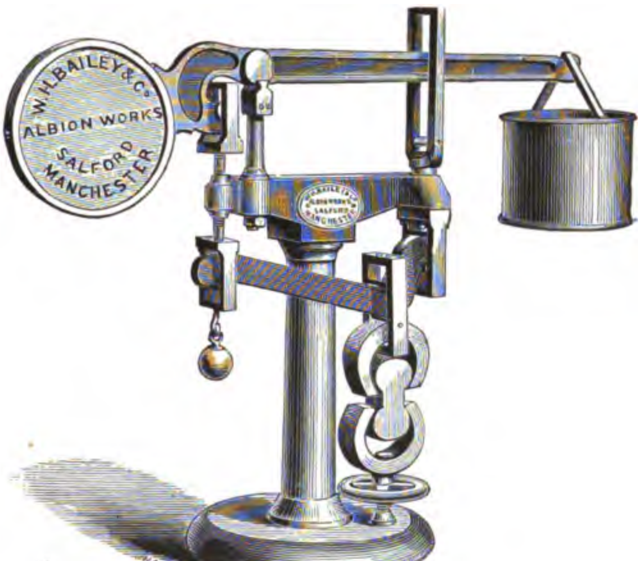


FIG. 166.—BAILEY'S HAND MACHINE FOR CEMENT TESTING.

15 per cent. of the weight of cement tested. It is important in this connection that not only should the number of meshes to the square inch in the sieve be given, but also the thickness of the wire used.

In the German standard rules for testing Portland cement, it is stated that the fineness must be such that not more than 10 per cent. residue is left after the cement has passed through a sieve having 5,806 meshes to the

square inch. In the French Government specification the residue is limited to 20 to 25 per cent. on a sieve of 32,256 meshes per square inch; that is about what is known as a 180 mesh, or 180 meshes each way along the side of the square inch.

It is further stated in the German rules that the wire must have a diameter equal to one-half the width of opening. The sieves in general use vary in fineness from 50 to 180 to the linear inch.

A rough test for fineness used by the millers consists in sieveing a certain volume of cement, determined by filling a standard vessel. The residue from this quantity is then measured in a vessel having a volume one-tenth of the first and divided horizontally into ten equal parts, each of which of course represents a percentage.

173. **Tensile Strength.**—Tensile tests may be made of samples of neat cement or a mixture of cement and sand. The test pieces are usually in the form of briquettes similar to those shown on Fig. 163. These forms of briquettes, or very similar ones, have come to be the standard shapes, giving the most uniform and reliable results. Various sizes are used, but by far the most usual is one giving a breaking section of 1 sq. in. The preparing of a set of these briquettes requires a certain amount of skill and experience, and should not be intrusted to anyone who has not had the necessary training.

The briquettes are formed in metal moulds, either made singly or in sets of five or more. In gauging the sample, a weighed quantity of cement is to be mixed with a certain definite percentage of water—either a prearranged percentage or the percentage which has been found most suitable for the particular cement in question. This can be found by gradually adding water from a known quantity until the cement has absorbed sufficient to work it up into a thick paste, and to cause the water to rise to the top of the pat when the trowel is drawn over it. The cement and water should be thoroughly mixed and worked together with a trowel, the water being added gradually until the required consistency is reached. The theoretical quantity of water required for chemical combination is somewhere about 8 or 9 per cent., but a

larger quantity is actually required in practice. So long as there is sufficient water present to satisfy the chemical requirements, the smaller the quantity of water the higher the tensile breaking load will probably be. The actual

FIG. 167.—BAILEY'S WATER LOAD MACHINE FOR CEMENT TESTING.

percentage of water used for neat cement varies from 16 to 25 per cent.

When the cement has been gauged—that is, the water thoroughly worked into it—it must be put into the moulds and well forced in with a wooden rammer, the cement being smoothed off level with the top of the mould. The

briquettes ought to be thoroughly set before they are taken out of the moulds. This is best done by using moulds which open, so as to obviate the forcing out of the briquette. The most convenient moulds are those which are fixed in a frame, so that the ramming does not force out the cement and cause the mould to lift.

The briquettes should be kept 24 hours in air after gauging, and then placed in water for a stated time, such as 7, 14, 28 days or more, before testing.

When the time for keeping the briquettes in water has elapsed they are to be taken out and broken in a tension machine by applying the tension load until fracture takes place. Generally speaking, the tensile strength increases with the time which is allowed to elapse between gauging and testing, that is, if the cement is from a good sample. A faulty cement may yield good results after a week, and show signs of deterioration after a further lapse of time.

Besides neat cement—that is, cement alone worked up with water—tests of a mixture of sand and cement are frequently made. In these tests the cement is mixed with a definite amount of sand in gauging, the most usual proportion being three parts of sand to one of cement, the minimum quantity of water being found by trial as in the case of neat cement. The sand used for this purpose should be clean, uniform, coarse sand, thoroughly washed. In the great majority of cases a standard sand from Leighton Buzzard is used. This is supplied ready for use, having been washed and screened so as to pass a 20 to the inch sieve and to be retained by a 30 to the inch sieve. The treatment is otherwise the same as in the case of neat cement.

Having regard to the fact that cement is never used neat in works of construction, but always mixed with some quantity of neutral matter, it is held by many authorities that briquettes made of sand and cement yield more reliable results than do those of neat cement.

The machines used for tension tests of cement briquettes are of very simple construction; in fact, any ordinary tension machines, such as those previously described in these pages,† may be used so long as they are

† See pages 69, 89, 259, and 260.

provided with appliances for holding the briquettes. It is preferable to have an automatic gear for increasing the load.

On Fig. 164 is represented a special machine by Messrs. Bailey for cement testing. It will be seen that this is a multiple-lever machine, provided with suitable holders for taking the briquettes. The load is applied by small leaden shot being allowed to run from a stationary reservoir into a can suspended at the outer end of the weighing lever. When the sample breaks, an automatic catch stops the flow of shot, and the contents of the lower can are put into a weighing scale (as shown in Fig. 165), which is calibrated to give at once, by its reading, the breaking load on the specimen. A similar machine in which the shot has to be supplied by hand is shown on Fig. 166. There are also a pair of cement moulds shown which are not quite the same shape as that on Fig. 163, but have the form used in the German laboratories. A third machine (Fig. 167), also by Messrs. Bailey, works with water instead of shot, and the breaking load is given by the height of the water in the suspended can when fracture takes place.

Messrs. Adie supply a single-lever machine provided with an automatic arrangement by which the poise weight is moved outwards at a uniform rate.

In addition to the care required in gauging the cement and filling the briquette moulds, a considerable amount is necessary in testing them. They must be placed in the holders so that the pull may come on the specimen evenly on the two faces, so that the stress is quite uniformly distributed on the cross section of the briquette. Then the load should be applied steadily at a uniform rate, all shocks and vibrations being carefully avoided. As soon as the briquette has fractured the breaking load should be at once booked. It is the custom with many people to write the breaking load on each half of the broken specimen in pencil to prevent any possibility of mistake.

174. Crushing Strength.—Crushing tests are generally made on 3in. or 4in. cubes, both of neat cement and sand and cement, gauged in the same way as the briquettes.

The crushing load may be obtained in any ordinary testing machine provided with compression plates, or a special machine may be used. One of these, by Messrs. Bailey, is shown on Fig. 168. This is an hydraulic press in which the load is increased by a screw plunger worked by hand as shown. The cube is fixed tight between the compression plates by the adjusting screw shown, which is also worked by hand. The load on the specimen is given at once by the position of the pointer of a pressure

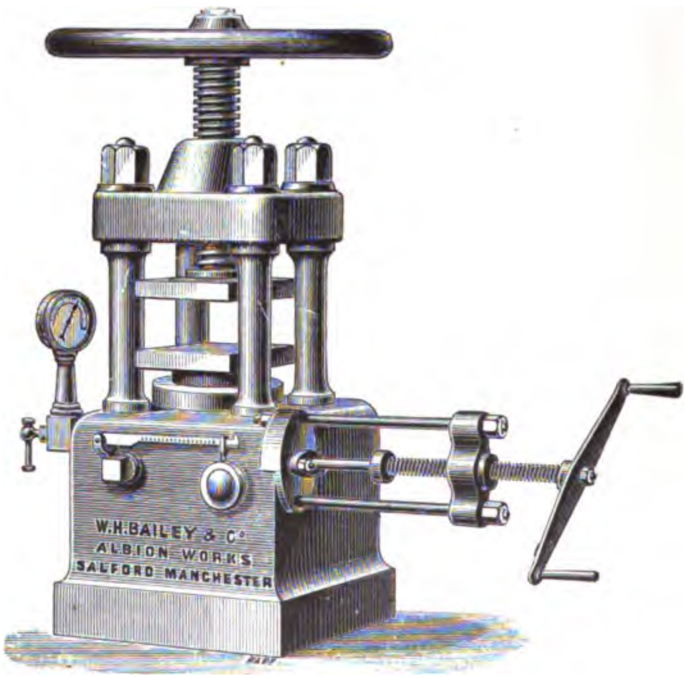


FIG. 168.—TESTING MACHINE FOR COMPRESSION CUBES OF CEMENT.

gauge, which is arranged to retain its maximum position after the specimen has failed by crushing. The fluid used in these machines is glycerine or oil. Messrs. Bailey make this machine in three sizes, suitable for working up to maximum loads of 12, 60, and 150 tons respectively.

Bedding Compression Specimens.—The most important point to be noted in testing cement or other brittle

substances in compression is the manner in which the specimens are bedded on the compression plates. What is required is an even distribution of the load over the top and bottom surfaces of the block, so that the compressive stress may be quite uniform. It is only when the stress is thus uniform that a reliable result can be obtained, as a very little extra stress on one side or the other will soon cause the material to chip away on that side.

Various methods have been employed for this purpose. Thick paper or cardboard is sometimes used, but this is not an altogether satisfactory way of bedding. Metallic sheet lead has also been used, but the effect is to compress the lead and cause it to spread, and in doing so to drag the surface of the specimen outwards and cause failure at a much lower load than that due to uniform crushing alone.

The most satisfactory way of bedding compression specimens is by using plaster of paris. The compression plates must first be cleaned and possibly oiled to prevent the adhesion of the plaster of paris. Then the plaster is mixed in sufficient quantity to the consistency of a thin paste. Some of this must now be spread with a trowel on the lower compression plate, so as to be not less than about a quarter of an inch thick and covering rather more than the area of the bottom of the specimen. The specimen is now placed quickly in position on the cement and the top plate screwed down tight, so as to thoroughly squeeze out any superfluous plaster. After a few minutes this plaster will have set sufficiently to allow the top plate to be lifted. The top of the block is now smeared with plaster until it is quite covered, and the top plate again screwed down tight. After about five or ten minutes the block will be ready for testing.

This latter consists in simply increasing the load steadily until the material fails, which it generally does with comparative suddenness, little warning being given by cracking of the material that failure is to be expected. The failure is generally expressed as so many pounds or tons per square inch or square foot of area required to produce failure.

The shape of the fractured specimen in most cases takes the form of two more or less perfect pyramids in the case of cubes, and cones in the case of cylinders.

175. Tests for Soundness.—The most common test for soundness consists in making pats of the cement with the minimum quantity of water necessary to produce a satisfactory paste, spreading the pats on a piece of clean glass, and tapering off the edges. When set, these are placed some in water and some in air and kept for a week, and then inspected to see if any cracks or changes in shape have developed themselves. This test is held by some to be unsatisfactory, because the pats may appear perfectly satisfactory at the end of a week, and yet show signs of deterioration when the offending lime has had time to do its work. It is, therefore, advisable to keep the pats for a longer time, and inspect them at intervals.

In what is known as the Faija test, introduced by the late Mr. Henry Faija, an artificial age is imparted to the pats by subjecting them when newly made to a moist heat of 100° Fah. or 105° Fah. for six or seven hours, and then placing them in warm water at about 115° to 120° for 18 hours longer. In all about 24 hours are taken over the test.

176. Setting Properties.—The setting of cement may be divided into two stages, namely, the "initial set" and the "permanent set." The former of these is that point when the crystallisation has caused a uniting of the particles to such an extent that the paste will no longer flow, and has changed its condition of partial fluidity for that of a solid. This point may be tested for by placing a pat of the newly-mixed cement paste on a sheet of glass, and noting the point when no movement will take place on the plate being shaken or tapped. Another test for the same purpose, adopted in the French Government Specification, is as follows: "A portion of the pat made shall be taken, and a cylindrical metal box, 1½in. in height and 3·4in. diam. filled with it. The box will then be shaken lightly for a few seconds, and the water which this shaking brings to the top shall be left on the cement. A prismatic needle weighing 10·5oz., and having a square section of one 0·039in., is then suspended over the box by a string passing over a pulley. The moment when the mass no longer allows the needle to penetrate to the bottom when lowered slowly and with caution will be considered as the

time of initial set. The setting will be considered as finished when the surface of the cement supports the needle without its penetrating to any appreciable degree."

The time of initial set varies from one to 20 minutes, and that of complete set from four to 120 minutes.

The process of setting causes the cement to rise in temperature, the extent of this rise being ascertained by mixing some cement and water in a small vessel, placing a thermometer in the paste and watching the mercury. Mr. Deacon used this method to ascertain the setting properties of the cement he used on the Vyrnwy dam. According to his own statement, "if within 15 minutes, the rise of the thermometer exceeds 2° Fah., or, within 60 minutes, 3° Fah., the cement is further exposed before use."*

As examples of the results given by samples of cement subjected to the above tests, the figures on p. 338 may be quoted. These results are given by Mr. D. B. Butler in his paper on "The Finer Grinding of Portland Cement,"† and are illustrative of some experiments on the properties of cement as delivered by the manufacturer, and the same cements after being much more finely ground. The three kinds of cement dealt with are F, from the lias districts of Warwickshire, G, from the Northfleet shore of the Thames, H, from the Grays shore of the Thames, and I, from the Medway.

‡ Prof. Unwin quotes the following figures obtained by Bauschinger from crushing tests of neat cement and of cement and sand.

	Pounds per square inch.
Mean crushing strength of neat cement, seven days after gauging	1,800
Do. for cubes of one part cement to three parts sand	825
Do. for cubes of one part cement to five parts sand	500

Where the time of testing is longer than one week, the following has to be added.

The general equation is

$$y = c + d\sqrt{x - 1}$$

* Min. Proc. I.C.E., vol. cxxvi. † Min. Proc. I.C.E., vol. cxxxii.
‡ Unwin's Testing.

Cement.	How Treated.	Fineness-residue per cent., on Sieves of Meshes per Lineal Inch.			Setting properties		Percentage of Water used for gauging Briquettes.		Tensile Strength in pounds per square inch.									
									Neat Cement.					Three parts Sand to One part Cement.				
		180	76	50	Initial set. Mins.	Set hard Mins.	Neat.	Sand.	7 days	28 days	3 months	6 months	12 months	7 days	28 days	3 months	6 months	12 months
F	As received from manufacturer	33·0	16·0	4·0	15	90	21·66	7·81	483	572	623	662	653	183	276	383	440	482
F	Reground extremely fine...	2·5	Nil.	Nil.	4	60	25·00	9·38	498	541	538	531	506	347	452	564	599	637
G	As received from manufacturer	35·0	20·0	8·0	10	90	20·00	7·81	495	618	622	694	759	187	245	334	377	392
G	Reground extremely fine...	1·0	Nil.	Nil.	1	4	25·00	8·13	540	474	560	466	477	282	363	494	595	617
H	As received from manufacturer	28·0	11·0	4·0	8	60	19·16	7·81	445	493	584	663	706	167	230	312	373	399
H	Reground extremely fine...	0·8	Nil.	Nil.	2	5	26·66	8·13	433	501	514	482	535	287	364	508	585	599
I	As received from manufacturer	39·0	15·0	2·5	20	120	20·0	8·59	592	639	736	791	751	240	207	389	425	410
I	Reground extremely fine...	0·8	Nil.	Nil.	2	10	30·17	11·26	417	394	459	476	498	387	465	560	585	618

where y is the strength at the end of x weeks, c is the crushing strength at the end of one week, and d is a constant, which for the above cases has values of 339 for the neat cement, 312 for the three to one, and 274 for the five to one mixture.

Thus, take the case of neat cement, tested 10 weeks after gauging. Here c is 1,800, d is 339, and x is 10. So that

$$y = 1{,}800 + 339 \sqrt{10 - 1}$$

that is to say, a cement which has a compressive strength of 1,800lbs. per square inch at the end of seven days, will require 2,817lbs. to produce fracture at the end of 10 weeks.

For cement compression pieces it is noted that, as in tension, samples kept in water yield higher results than those kept in air; and also that in a good cement the strength should steadily increase with age.

The strength of neat cement cubes kept in water for four weeks varies from 5,000lbs. to 2,000lbs. per square inch. When mixed with sand the strength continually diminishes with the ratio of sand to cement.

Kirkaldy gives the following results of crushing tests of cubes of cement and sand:—

*KIRKALDY'S TESTS OF SAND AND CEMENT CUBES.

Composition.	Age days.	Crushing strength in pounds per square inch.
Neat	10	2,910
"	20	3,341
"	30	3.723
1 part cement, 2 parts sand ...	10	893
"	20	1,023
"	30	1.172
1 part cement, 3 parts sand ...	10	408
"	20	494
"	30	593
1 part cement, 4 parts sand ...	10	228
"	20	275
"	30	385

* Kirkaldy's "Testing."

CONCRETE, STONE, BRICK, AND OTHER BRITTLE MATERIALS.

177. With regard to the testing of these, there is little to be added to what has already been said in describing the tests of cement. The test applied to all these substances is almost invariably the compressive test. Fairly large specimens should be employed, in order to obtain reliable and uniform results, and, consequently, a large testing machine is required.

The specimens should be bedded, as in the case of cement, with plaster of paris set in place with the compression plates resting upon it.

The following are some examples of the crushing strength of stones, &c. :—

TABLE OF THE CRUSHING STRENGTH OF VARIOUS STONES, &c.

Material.	Authority.	Crushing Strength. Tons per square foot	Crushing Strength. Pounds per square inch
Portland Cement Concrete, 36 months old	Deacon	185	2,880
Portland Cement Concrete, one month old	Deacon	107	1,665
Granite, Aberdeen Grey	Unwin	1,412	22,000
„ Aberdeen Red	„	1,614	25,100
Basalt, Penmaenmawr	Fairbairn	1,086	16,850
Sandstone, York Grit	Unwin	712	11,050
„ Red Mansfield	„	609	9,560
„ Red Alton	„	309	4,800
Limestone, White Italian Marble	Rennie	1,400	21,800
„ Portland	Unwin	516	8,020
„ Purbeck	Rennie	587	9,110
„ Ancaster	Royal Com.	150	2,330
„ Bramham Moor	„	380	5,900
Bricks, London stock, average	Unwin	140	2,180
„ Leicester, wire cut, average	„	290	4,500
„ Staffordshire Common Blue	„	400	6,210

TIMBER.

178. The tests to which a specimen of timber may be subjected are :—

Tension, generally along the grain;

Compression, both along and across the grain ;

Cross-breaking or bending;

Shearing, across the grain.

Tension.—A tensile test of a bar of wood is not altogether satisfactory, considerable difficulty being experienced in holding the piece so that there is little crushing of the ends and no shearing. If the ends are simply enlarged, as in a metal-plate specimen, it is probable that the parallel portion will be sheared out of the enlargement. One of the most satisfactory ways of forming the specimens so as to go in ordinary wedge holders is to make the piece parallel to begin with, and then diminish the cross section of the middle to a small extent only, the smaller section being approached by very gradual curves.

Compression Tests are generally carried out on cubes or short cylinders of the wood, care being taken that the ends which come in contact with the compression plates are quite parallel. If the ends are rough, millboard may be used as a bedding material.

Cross-breaking.—This is easily carried out, and is probably the most satisfactory kind of test to which it is possible to subject timber. In testing a beam of timber on knife edges care must be taken to interpose small pieces of thin iron or steel plate between the specimen and the knife edges, to prevent penetration of the knife edges and the consequent damage to the material.

A very convenient way of expressing the strength of a timber beam is to give the number of pounds required to fracture a beam 1in. broad, 1in. deep, and 1ft. span, assuming the truth of the ordinary beam formula; in this way beams of different sizes may be compared.

The modulus of elasticity of timber can easily be determined by making use of one of the appliances mentioned in paragraph 104, or by applying an extensometer to a tension specimen.

In the following table are given the strength properties of some of the timbers, as collected from various sources:

STRENGTH PROPERTIES OF VARIOUS KINDS OF TIMBER.

Timber.	Tensile strength. Tons per square inch.	Crushing strength. Tons per square inch.	Breaking strength of a rectangul'r beam, 1in. square and 1ft. span.	Authority.
Ash	7·6	4·0	700lbs.	Anderson
Beech	from 10 to 5·1	3·8	650 ,,	,,
Elm	about 6·0	4·0	400 ,,	,,
Fir, American	3·4		524 ,,	,,
,, Memel ...	4·9	from 3·0 to 2·4	561 ,,	,,
,, Riga......	5·6		457 ,,	,,
Oak, English ..	6·7	3·7	590 ,,	,,
,, Canadian	5·4	3·5	580 ,,	,,
Teak	5·2	5·3	814 ,,	,,
Greenheart ...	3·3	5·4	835 ,,	Thurston

The strength of timber is so very variable, on account of differences in age, climate, soil, time of felling, and seasoning, that the above figures must not be taken as in any way conclusive, but only as rough guides to the results that may be expected from tests. With the exception of the last set, the figures are all taken from Anderson's book, and are, originally, from the experiments of Barlow, Bevan, Muschenbrock, and Tredgold.

Thurston gives the values of the modulus of elasticity for timbers as varying from 447 tons per square inch in the case of white pine to 937 for teak, the mean value for 16 different kinds of timber being 681 tons per square inch, or 1,525,000lbs. per square inch.

CHAPTER XIII.

STRENGTH PROPERTIES OF THE PRINCIPAL MATERIALS OF CONSTRUCTION.

In the present chapter the strength properties of the chief materials used for engineering purposes, so far as they have not been referred to up to the present, will be briefly discussed, and standard test results given.

IRON AND STEEL.

The most important materials used for constructive purposes at the present day are the carburets and alloys of iron. These are usually classed as either *wrought iron*, containing little or no carbon; *steel*, containing rather more carbon; and *cast iron*, which has the largest percentage of carbon. Each of these three contains so many different varieties that a more detailed classification is necessary, such as the following:—

CLASSIFICATION OF IRONS AND STEELS.

(1) **Wrought Iron.**—Consisting of iron containing not more than 0·35 per cent. of carbon. It has a fibrous fracture and is tough; very malleable at high temperatures, and partly so at low temperatures; is not susceptible to hardening effects to any appreciable extent. Produced either by puddling or a crucible process, in three or more grades.

(2) **Steel.**—Consisting of iron containing from 0·35 to 1·50 per cent. of carbon; malleable at a red heat, and partly so when cold; is non-fibrous and tough; is more easily fusible than wrought iron; and those steels high in carbon, or hard steels, possess the power of hardening when heated or quenched. But this property is only

possessed to a very slight extent by the low carbon or mild steels.

The steels may be divided into :—

Mild or *soft* steel, containing 0·35 to 0·60 per cent. of carbon.

Hard steel, containing 0·60 to 0·80 per cent. carbon.

Hardest steel, containing 0·80 to 1·50 per cent. carbon.

Each of the above is produced in three or more grades. Besides these simple steels, there are several special steel alloys, consisting of carbon steels alloyed with a third constituent. These are :—

Chrome steel.
Manganese steel.
Nickel steel.
Tungsten steel.
Aluminium steel.

(3) **Cast Iron.**—Consisting of iron and 1·50 to 6·00 per cent. of carbon, as well as small quantities of manganese, silicon, sulphur, and phosphorus; non-malleable at any temperatures, easily fusible, and not capable of being hardened or tempered in the ordinary way.

Cast irons may themselves be divided into :—

(A) *Foundry Pig.*—Containing carbon, phosphorus and silicon.

(B) *Forge Iron.*—Containing carbon, sulphur, and phosphorus, and little silicon and manganese.

(C) *Spiegeleisen.*—Containing chiefly manganese and silicon.

These alloys and carburets of iron will now be considered in detail.

THE STRENGTH OF WROUGHT OR MALLEABLE IRON.

179. Of the various alloys and mixtures of iron used in the arts, what is known as *wrought iron* is chemically the most pure, usually containing about 99·5 per cent. of chemically-pure iron The other ingredients are: Carbon, of which there should not be more than 0·20 per cent. present; silicon, which should not exceed 0·20 per cent.;

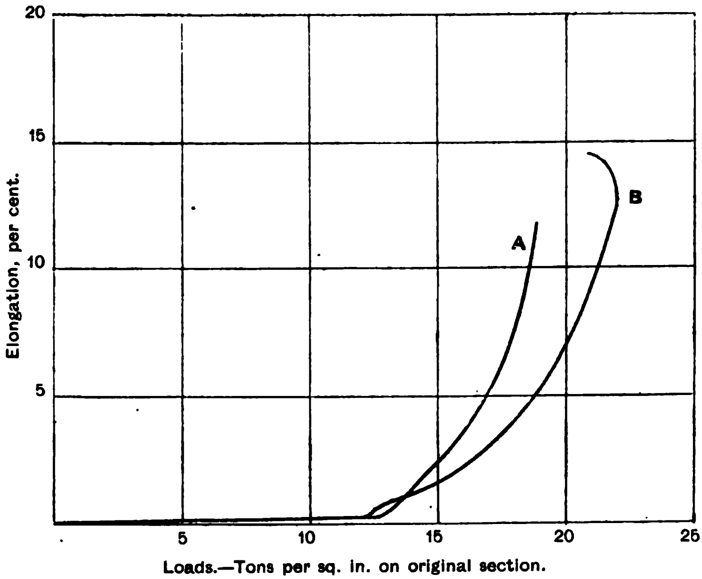


FIG. 169.—TENSION LOAD-STRAIN DIAGRAMS FOR WROUGHT IRON.
A—Lowmoor plate; B—High grade bar.

sulphur, phosphorus, and copper. If carbon or silicon exist in the iron in greater quantities than those named the iron will approach the condition of steel, and will be rendered harder and less reliable. Sulphur and copper, even in very small quantities, render the metal "hot short," and difficult to work, while phosphorus has the effect of making the iron "cold short," that is to say, greatly lacking in ductility at the ordinary temperatures.

There is a wide range in the varieties of wrought iron which are produced, varying from the highest quality Yorkshire irons—with a comparatively low tensile strength of from 20 to 23 tons per square inch, with an elongation on 10in. of 30 per cent., and reduction of area of over 40 per cent.—to the "common" merchant iron with a tensile strength of 22 tons per square inch or more, extension of from 12 to 2 per cent., and a reduction of area of from 20 to 5 per cent.

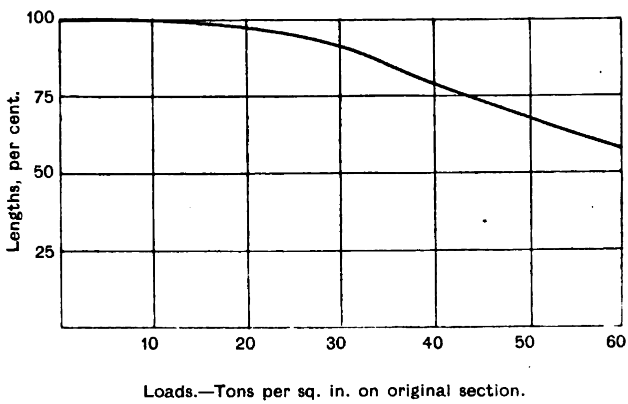


FIG. 170.—COMPRESSION LOAD-STRAIN DIAGRAM FOR SPECIMEN OF LOWMOOR IRON 1IN. DIAM. AND 2IN. LONG.

Wrought iron is characterised by the fibrous fracture which it exhibits under a tension test. This fracture may have a uniform, fine fibrous appearance, as in the best brands, or the fracture may be wholly or in part crystalline and laminated. The lamination is caused by the process of manufacture, and may be due to the presence of slag in thin layers, which prevents the metal from being properly united. The crystalline appearance may be in some cases caused by the sudden application of the load.

The following table exhibits some of the strength properties of a number of brands of wrought iron as given by different authorities :—

WROUGHT IRON. TENSION AND COMPRESSION.

Description.	Tension.				Compression.		Authority.
	Limit Stress. (Tons per square inch.)	Maximum Stress. f_t (Tons per square inch.)	Percentage Extension.	Percentage Reduction in Area.	Ratio Length. / Diameter.	Yielding Stress. f_c Tons per square inch.	
Netherton Crown, "Best"	15·04	21·60	—	—	—		Platt and Hayward
Netherton Crown, Rivet Iron	16·82	25·01	—	—	-		Platt and Hayward
S. C. Crown, Wrought Iron	17·13	24·56	—	—	—	-	Platt and Hayward
	15·66	23·44	—	—	—		Popplewell and Coker
Lowmoor (a)	14·00	28·95	7·01	5·9		13·33	The Steel Committee
Lowmoor (b)	11·80	24·79	12·65	48·8	-	11·50	The Steel Committee
Yorkshire	13·16	23·69	17·87	51·4		13·00	The Steel Committee
S. C. Crown	11·83	22·63	17·50	47·7		11·66	The Steel Committee
Lowmoor Iron	12·50	22·10	local 6·67	—		-	Stromeyer
Iron Ship Plates	—	22·01	10in. 5·7	5·4			Board of Trade Report
Iron Boiler Plates	—	21·15	9in. 9·6	13·07		-	Board of Trade Report
,, ,, †	—	18·48	10in. 3·2	4·41		-	Unwin
Prussian Plates, Annealed	12·73	22·53	24·70	—		---	Kirkaldy
Prussian Plates, Unannealed	13·00	23·40	23·80	—		-	Kirkaldy
Prussian Plates, Annealed ‡	12·04	21·70	15·10	—	-		Kirkaldy
Prussian Plates, Unannealed †	12·60	22·70	14·60	—	-	-	Kirkaldy
Swedish Hammered Bars	11·05	18·80	24·6 on 15in.	—	2–1	9·45	Kirkaldy
Best Lowmoor Bars	11·10	21·00	30·30	40·5	—	--	Bennett *
Treble "Best"	15·50	23·40	22·00	32·00	—	—	Bennett *
Bars, on 10in. length	—	24·06	24·30	46·1	—	—	Bennett *
Same, V-nicked	—	31·86	—	—	—	—	Bennett *

* I. M. E., 1886. † Across the Fibre. ‡ With the Fibre.

The above values are for tension and compression. It will be observed that the failing stress in compression, which is really the elastic limit, is not very different from the elastic limit stress in tension. The strength of ship and boiler plates is less when tested across the fibre than with the fibre, the difference amounting to from 1 to 1·75 tons per square inch.

The two bars tested by Mr. Bennett were cut from the same bar, the first turned for a length of 10in., and the second simply nicked down to the same diameter. The results obtained in this case are similar to those already given.

Typical load-strain diagrams for wrought iron in tension and compression are given on Figs. 169 and 170.

180. Mr. Stromeyer's Tests.—In the following table are given the results obtained by Mr. Stromeyer in tension tests of wrought iron which had been treated in different ways :—

Particulars.	Elastic Limit. Tons per sq. in.	Maximum Strength. Tons per sq. in.	Local Elongation. Per cent.
LOWMOOR IRON.			
Unprepared	12·5	22·1	6·67
Quenched red-hot in cold water	...	24·5	7·02
Annealed blue-hot two nights...	13·4	21·7	18·71
,, ,, four ,, ...	14·1	22·1	14·16
Bent cold to a radius of 15in. and flattened...	14·1	23·2	18·78
Bent hot (blue to straw) and flattened	12·5	23·6	7·06
Twisted cold (90° in 12in. and back)	15·2	23·2	8·46
Twisted hot (blue to dark straw and back)	16·3	24·6	16·33

181. Elastic Moduli for Wrought Iron.—The modulus of elasticity in tension of wrought iron varies from 12,200 to 13,500 tons per square inch in most cases; these values correspond to 27,400,000lbs. and a little over 30,000,000lbs. per square inch.

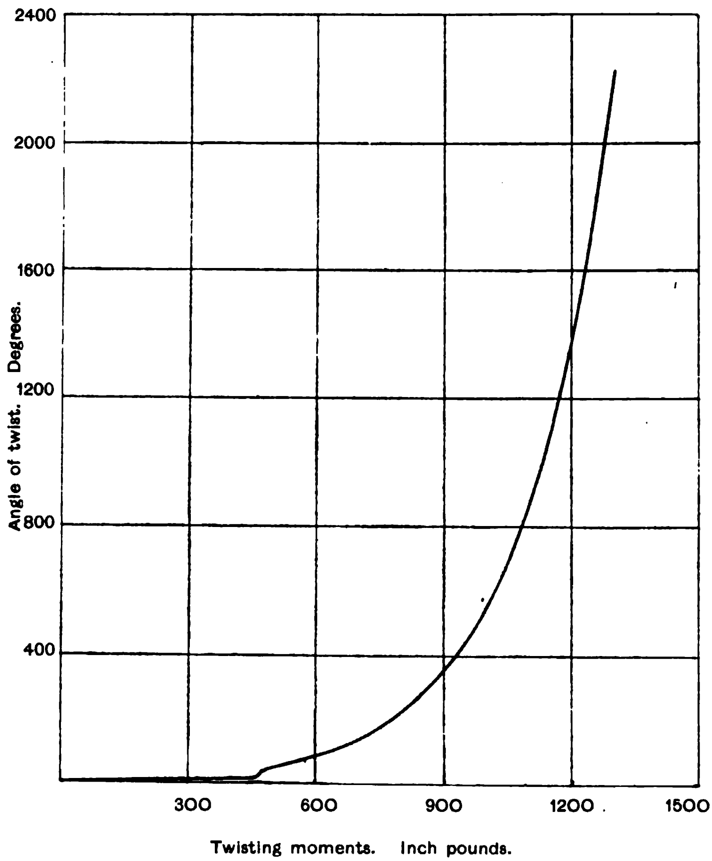


FIG. 171.—TORSION, LOAD-STRAIN DIAGRAM FOR WROUGHT IRON.
Shaft 5in. long and 0·469in. diam.

The modulus in compression is, if anything, slightly less than in tension for the same material, the ratio being about 1·03 to 1·00.

The third column in the following table contains some values for the modulus of rigidity, as obtained from torsion experiments :—

Elastic Constants for Wrought Iron.

Kind of Iron.	Elastic Moduli. Tension E.	Compression E.	Torsion G.	Authority.
	Tons per square inch.			
Netherton Crown "Best"	12,650	...	5,720	Platt and Hayward.
Netherton Crown, Rod	12,820	...	6,120	
S. C. "Crown"	12,940	...	6,230	
Merchant Bar	13,603	...	...	Author.
Burden's Best	13,220	12,740	...	Ricketts.
Lowmoor Iron	14,280	...	...	Knut Styffe.
Dudley Iron	12,870	...	...	Unwin.

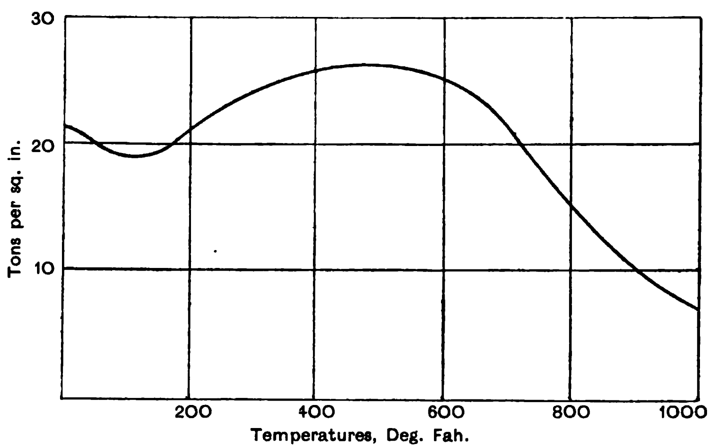


FIG. 172.—ULTIMATE STRENGTH OF WROUGHT IRON AT DIFFERENT TEMPERATURES (JOHNSON).

182. Wrought Iron in Shear and Torsion.—Comparing the values of shearing strengths, as obtained from direct shearing tests, with the tension strengths of the same

irons as shown in the following table, it will be seen that the ratio varies from 0·76 to 0·87.

Calculating the coefficient of torsional strength by the usual torsion formula—which assumes perfect elasticity up to the point of fracture—from the ultimate twisting moments, it will be seen that in all cases the value is much larger than the shearing strength obtained from

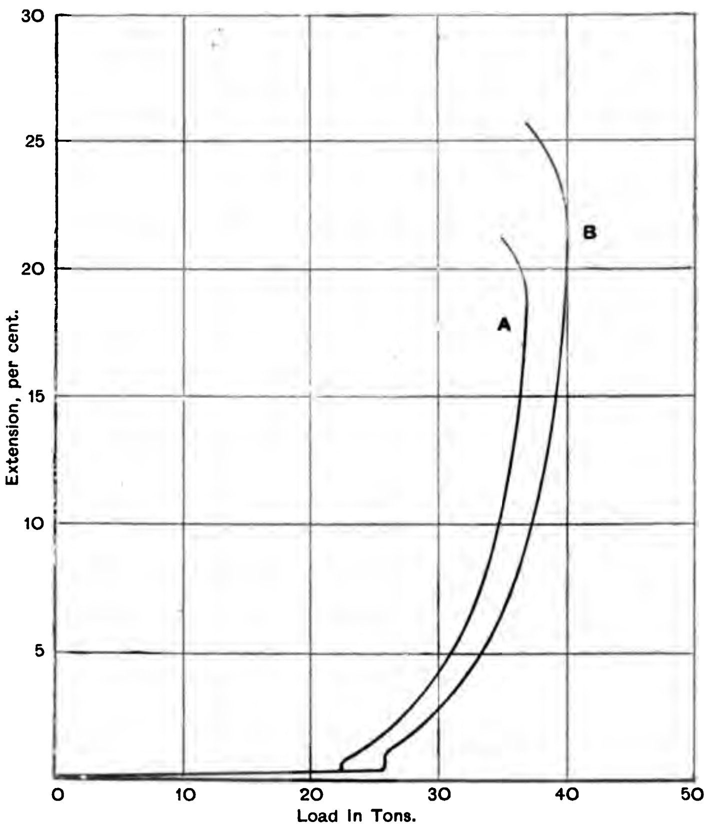


FIG. 173.—LOAD-STRAIN CURVES FROM MR. GROVER'S TENSION TESTS. A—UNCOMPRESSED; B—COMPRESSED AND ANNEALED.

direct tests. This discrepancy is caused by the false assumptions made. That the condition of a ductile material approaches that of perfect plasticity at the point of fracture in torsion—a condition involving a uniformity of torsional stress at every point of the section of the bar—is shown by calculating the coefficient of torsional

strength from the second formula, which assumes a uniformity of stress over the section. (See par. 16, p. 41.) The results are shown in the fifth column of the following table; they agree very well with the direct shearing strengths:—

WROUGHT IRON IN SHEAR AND TORSION.

Material.	f_t Ultimate Tensile Stress.	f_s Ultimate Shearing Stress (direct).	Ratio $\frac{f_s}{f_t}$	Coefficient of Torsional Strength $f_T = \frac{2}{\pi}\frac{T}{R^3}$	Coefficient of Torsional Strength $f_{T1} = \frac{3}{2\pi}\frac{T}{R^3}$	Authority.
	Tons per sq. in.	Tons per sq. in.		Tons per sq. in.	Tons per sq. in.	
Netherton Crown, best	21·60	18·76	0·87	25·20	(18·90)	Platt and Hayward.
Netherton Crown, rivet	25·01	21·21	0·85	28·87	(21·60)	
S.C. Crown	24·56	20·72	0·85	29·50	(22·10)	
Merchant Bar, solid	23·44	20·37	0·87	28·85	21·64	Popplewell and Coker.
Merchant Bar, hollow	23·44	20·37	0·87	24·17	20·39	
Swedish hammered iron	18·80	15·20	0·81			Kirkaldy.
Rivet iron	22·06	16·96	0·77	Single Shear.		Talbot.
Do.	22·06	16·90	0·76	Double Shear.		
Hammered iron	23·62	17·6	0·74	25·70	(19·30)	Kirkaldy.
Do.	23·35	17·3	0·74	23·85	(17·90)	

On Fig. 171 is a load-strain diagram from a wrought-iron shaft tested by the author.

183. Effect of Temperature on the Strength of Wrought Iron.—Variations of temperature affect the strength properties to a considerable extent.

As the temperature to which the test bar is exposed during a tension test increases, the ultimate strength of wrought iron increases steadily up to about 450° to 500° Fah., when it begins to diminish again, which it continues to do up to the highest temperatures which have been tried, viz., about 1,600° Fah. The rate of increase and decrease is shown graphically on Fig. 172.

The elastic limit follows somewhat the same kind of variation, except that the maximum strength is reached earlier, at about 120°.

The ductility of wrought iron, as shown by the ultimate extension, decreases until a temperature of nearly 300° is attained, when it again begins to increase.

The modulus of elasticity continually diminishes to a small extent as the temperature increases. Johnson gives this variation as 2 per cent. decrease for every 100° increase in temperature.

FIG. 174. FIG. 175.

184. The Effect on Wrought Iron of Previous Compression beyond the Elastic Limit.—This point has been investigated recently by Mr. F. Grover, by means of experiments on iron which had previously been compressed during the process of closing tyres on wooden wheels by West's process.* In this process, the tyre, which is slightly larger than the wheel to begin with, is "set" or compressed in place to the proper diameter by a series of radial hydraulic rams pressing uniformly on the outer periphery. The results of tension tests made by Mr. Grover on bars of the uncompressed metal, and also upon bars cut from the compressed tyres, are given in the accompanying table:—

* See pamphlet reprinted from "Engineer," September 3rd, 1897.

Tabulated Results of Mr. Grover's Tension Tests.

Uncompressed Bars.									Bars Cut from Compressed Tyres.											
Dimensions in inches.		Modulus of elasticity (E), million lb. sq. in.	Elastic limit in tons per sq. in.	Maximum load in tons per sq. in.	Ratio of limit to maximum load.	Extensions, per cent. on		Reduction of area, per cent.	Dimensions after pressing.		Modulus of elasticity (E), million lb. sq. in.	Elastic limit in tons per sq. in.	Maximum load in tons per sq. in.	Ratio of limit to maximum load.	Extensions, per cent. on			Reduction of area, per cent.	Maximum reduction in diameter of tyre, per cent.	Remarks.
Breadth.	Thickness.					2in.	10in.		Breadth.	Thickness.					2in.	8in.	10in.			
2·06	0·76	28·0	14·4	23·6	60·9	22·6	19·5	19·08	2·12	0·78	27·7	20·6	22·7	90·7	0	—	0·02	0	6·97	Merchant iron, "Thornhill B." Fig. 174.
									2·12	0·78	—	15·2	25	60·9	27·5	16·5	—	17	—	Same as above, annealed. Fig. 175.
2·55	0·766	28·1	14·3	24·1	59·4	30	19	28·7	2·50	0·769	24·5	17·8	24·8	71·7	13·0	—	4·8	9·5	3·49	See fracture, Fig. 176.
2·308	0·755	—	14·0	22·5	62·3	23	15·5	19·3	2·4	0·78	—	22·1	28·3	83·9	0	—	0	0	10·5	Same fracture as Fig. 174.

The conclusions arrived at from these tests are :—

(1) That high compressive strains applied to iron bars result in raising the limit of elasticity in tension, and that the tension limit may be changed from 61 to 91 per cent. of the maximum tensile strength by increasing the intensity of the compressive stress applied.

(2) That the tension modulus of elasticity is slightly lowered by the application of a high compressive stress.

(3) That a ductile iron bar presenting a perfectly fibrous fracture will, after the application of excessive compressive stress, be entirely changed to give a fracture

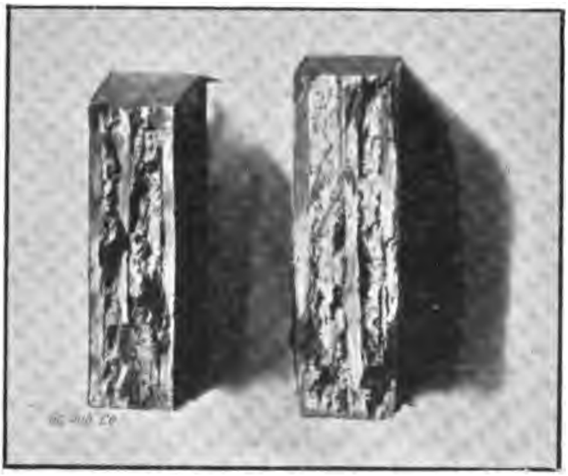


FIG. 176. FIG. 177.

of 100 per cent. crystalline area, almost similar in appearance to that of cast iron. That the proportion of fibrous to crystalline area is diminished as the compressive stress is increased.

(4) That annealing a compressed bar restores it to a fibrous state.

On Fig. 173, the curve marked A is that of a specimen of the uncompressed iron ; its fibrous laminated fracture is shown on Fig. 175.

The curve B is for a specimen cut from a compressed tyre, and straightened cold. The fracture of this bar is

shown on Fig. 174, and it will be noticed that it is similar in appearance to that of a fine-grained cast iron. On annealing a broken half of this bar, and again testing it, the fracture was restored to the appearance of Fig. 175. The compression stress on this tyre, 26 tons per square inch, was in excess of that required.

The fractures, before and after treatment, under a more moderate compression, are shown on Figs. 176 and 177.

THE STRENGTH OF STEEL.

185. As regards its chemical constituents, steel occupies a position midway between wrought iron, which may be regarded as commercially pure iron, and cast iron, which contains a comparatively large proportion of carbon, either combined or mechanically mixed. The percentage of carbon present in cast iron varies from 1·5 to 6·0 per cent., and in steel begins where cast iron ends, the hardest containing 1·5 per cent. of carbon, and the softest kinds about 0·1 per cent.

Steel may be broadly divided into two classes, viz., "hard" or "cast" steel, used in the manufacture of tools of various kinds, and springs; and what is known as "mild steel," employed in the construction of boilers, bridges, ships, and most large metallic structures. The former of these two classes is generally made by the carburisation of bars of wrought iron, afterwards melted in crucibles, cast into ingots, and forged and rolled into bars. On the other hand, the mild variety is made by several processes, in all of which cast iron is decarburised. Briefly, the processes used in the production of mild steel are as follows :—

(*a*) **The ordinary Bessemer** process, in which the silicon and carbon are burnt out of the cast iron, and afterwards a sufficient amount of carbon is added in the form of ferromanganese or some other compound of iron, carbon, and manganese. In this process the converter or vessel in which the process is carried out is supplied with an acid lining.

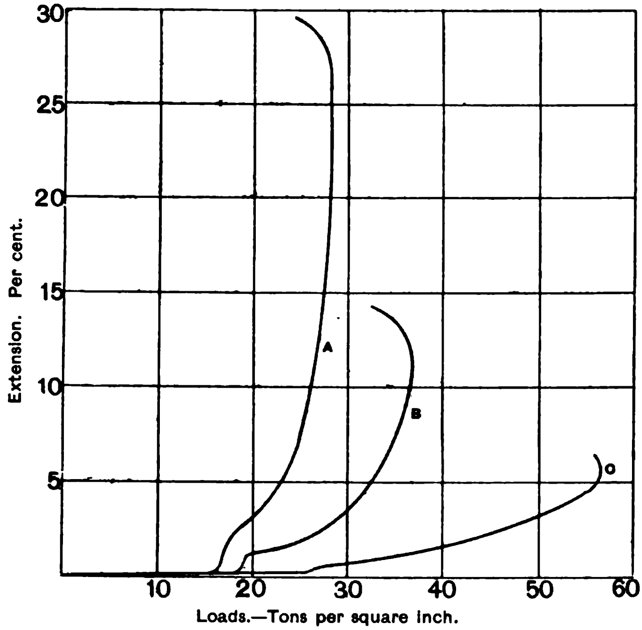


FIG. 178.—TENSION LOAD-STRAIN DIAGRAMS FOR STEEL

A.—Low carbon bar steel.
B.—Annealed tool steel. } Johnson.
C.—Unannealed tool steel.

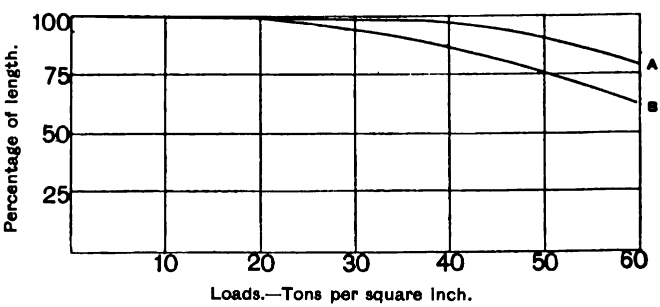


FIG. 179.

A.—High carbon steel. B.—Mild steel.

(*b*) **The Bessemer basic** process, in which the converter is provided with a basic lining, which allows of the use of pig iron containing a moderate percentage of phosphorus, which is not possible in the ordinary Bessemer process.

(*c*) **The Siemens-Martin** process, in which scrap wrought iron is fused at a high temperature in a bath of pig iron, the proportions being such that the resultant percentage of carbon is that of a soft steel.

(*d*) **The Siemens** process, in which a quantity of rich hæmatite ore is added to the bath of molten pig, so as to effect the decarburising of the cast iron.

These two latter processes are sometimes modified by the use of a basic lining to the furnace, in place of the acid lining usually employed, so as to allow of the use of phosphoric pig.

No definite line of demarcation can be laid down between hard and mild steels, the one merging imperceptibly into the other. The following may, however, be taken as the most characteristic qualities of the two kinds :—

HARD STEEL.	MILD STEEL.
Percentage of carbon, 6·0 to 1·5. Tensile strength and crushing strength high; ductility low; property of hardening and tempering; working requires considerable care as compared with mild steel.	Percentage of carbon, 1·5 to 0·1. Tensile and crushing strength lower; soft and very ductile; without the property of hardening or being tempered; requires less care in working than does hard steel, but more than wrought iron.

Typical load-strain diagrams for steel in tension and compression are given on Figs. 178 and 179.

Mr. Skelton* gives the percentage of carbon in the harder kinds of crucible cast steel as follows :—

* "Economies of Iron and Steel," Skelton.

Percentage of Carbon in Crucible Cast Steel.

Razor steel	...contains	1·500	per cent.	of carbon.
Hard file steel	,,	1·375	,,	,,
Turning-tool steel	,,	1·250	,,	,,
Steel for stocks, dies, &c.	,,	1·125	,,	,,
Graving-tool steel	,,	1·000	,,	,,
Wood-working chisel steel	,,	0·875	,,	,,
Spring steel	,,	0·500 to 0·550 per cent. of carbon (for railway vehicle springs).		

Mr. Skelton also gives the following as the strength properties of mild structural steel :—

Composition and Strength of Structural Steel.

	Carbon. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	Manganese. Per cent.	Ultimate strength. Tons per sq. inch.	Elongation on 8in. Per cent.
A	0·150	trace	0·043	0·060	0·600	28·87	24·5
B	0·140	trace	0·046	0·052	0·610	28·85	23·0
C	0·120	trace	0·050	0·050	0·580	27·28	23·3
D	0·100	trace	0·035	0·045	0·560	23·06	29·0

The figures marked A and B are from strips cut from plates. In the case of C it will be seen that the lower percentage of carbon is accompanied by a falling off in tensile strength; these figures relate to strips from plates ½in. thick. D is an extra soft steel for locomotive tubes.

186. Tensile Strength of Structural Steel (Campbell). The figures in the following table will give a very good idea of the chief properties of structural steel in tension. The figures are taken from Mr. Campbell's book on "Structural Steel" :—

Tensile Strength of Structural Steel.

Description of Steel.	Chemical Composition. Ph. Below Per cent.	Si. Per Cent.	Si. Per cent.	Mn. Per cent.	Average Tensile Strength Tons per square inch.	Average Elastic Strength Tons per square inch.	Extension per cent. on 8in.
Extra dead soft. Basic	0·04	0·04	0·06	0·05	22·01	13·25	27·50
Bridge rivets. Acid or basic open hearth ...	0·04		0·05	0·05	21·65	13·40	31
Hard bridge rivets	0·04	0·04	0·05	0·60	25·70	14·60	30
Common hard rivets ...	0·06	0·04	0·06	0·60	25·70	14·60	29
Soft bridge steel	0·06 to 0·04	0·06	0·07	0·50	24·60	14·25	24
Medium bridge steel	0·06 to 0·04	0·04	0·07	0·60	26·30	14·45	23
Hard bridge steel ...	0·06 to 0·04	0·05	0·07	0·80	28·10	14·90	21
Extra hard bridge steel	0·06 to 0·04	0·10	0·07	0·80	29·90	15·50	19
Forging steel	0·06 to 0·04	0·10	0·07	0·90	33·50	16·40	17
Hard forging steel ...	0·05 to 0·03	0·10	0·07	0·90	39·00	19·50	12·15
Soft steel castings	0·04		0·05	0·08	28·10	14·05	15
,, ,, annealed					26·80	13·40	20
Hard steel castings......					30·40	15·20	15
,, ,, annealed					29·00	14·5	15

Mr. Campbell also gives the following percentages of carbon which are usual for the chief kinds of steel :—

Kind of Steel.	Percentage of Carbon.
Tool steel	0·75 to 1·50
Spring steel............	About 0·50
Rail steel...............	0·40 to 0·45
Boiler-plate steel ...	0·25 to 0·30
Bridge steel	0·20
Very mild steel	0·10 to 0·15

187. Strength of Open-hearth Steel for Boilers.—In his paper on the above subject, Mr. Hamilton Goodall †

† Min. Proc. Inst. C.E., vol. xcii.

gives a number of results of tests in tension and shear, as well as many drifting tests. The following is an abridgement of the chief results :—

OPEN-HEARTH STEEL FOR BOILERS.

Material.	Elastic Limit. Tons per sq. inch.	Maximum Stress. Tons per sq. inch.	Elongation per cent.	Reduction in Area per cent.
Shell plate, $\frac{13}{16}$ thick, unannealed	14·09	26·87	On 8in. 23·73	45·30
Shell plate, $\frac{13}{16}$ thick, annealed	14·35	27·45	,, 22·38	48·95
Specimens cut from the welds of furnaces (average of six)	—	26·75	,, 24·6	—
Damaged plate	11·49	25·04	,, 25·0	57·67
Plate cut crosswise, unannealed	17·50	34·25	,, 15·62	17·92
Plate cut crosswise, annealed	14·75	33·00	,, 17·58	41·38
Plate cut lengthways, unannealed	15·00	32·75	,, 20·7	36·54
Plate cut lengthways, annealed	16·75	33·00	,, 20·70	43·77
Average of 183 American specimens	18·42	26·36	On 15in. 23·38	45·00

Tests of the same steel used in the earlier of the above tests in shear gave the breaking stress in shear, when tested lengthways, as from 19·8 to 29·66 tons per square inch; and for plates cut crossways, 19·75 to 20·72 tons per square inch.

These results give a ratio of ultimate shearing stress to ultimate tensile stress of about 75 per cent.

188. Strength of Tyre Steel.—The following results of tests by Mr. Arnold are given in his paper on "Bessemer Steel Tyres" ‡ :—

TESTS OF BESSEMER TYRE STEEL.

Composition. Per cent.						Tensile Strength. Tons per sq. inch.	Extension per cent. on inches.	Reduction in Area per cent.
C.	Si.	Mn.	S.	Ph.	Chromium.			
0·28	0·07	1·25	0·08	0·08	—	37·00	26 on 2in.	47
0·25	0·03	1·75	0·11	0·11	—	42·10	18 ,,	26
0·28	0·08	1·54	0·10	0·09	0·42	49·80	15 ,,	26
0·32	0·11	1·46	0·05	0·07	0·30	50·00	16 ,,	29
0·28	0·11	1·41	0·07	0·07	0·64	50·40	10 ,,	14

‡ From Min. Proc. Inst. C.E., vol. xcv.

The following figures were also obtained from specimens of the same material, the bars having different measured lengths :—

0·27	0·04	1·69	0·12	0·11	0·26	43·40	22·3 on 2in.	36·1
,,	,,	,,	,,	,,	,,	42·8	20·2 ,, 4 ,,	34·3
,,	,,	,,	,,	,,	,,	43·80	16·4 ,, 6 ,,	35·6
,,	,,	,,	,,	,,	,,	42·3	16·2 ,, 8 ,,	37·4
,,	,,	,,	,,	,,	,,	44·1	13·2 ,, 10 ,,	31·4

Comparative tests of unhardened and hardened specimens of the same steel :—

0·50 | 0·07 | 1·10 | 0·09 | 0·08			
Unhardened	50·8	14·9 on	31·4
Water hardened	69·4	10·9 ,,	30·0
Oil hardened..................	88·0	3·1 ,,	4·9

In the discussion on the above paper, Mr. Kirkaldy‡ quoted the following results of tests on various grades of tyre steel :—

KIRKALDY'S TESTS OF TYRE STEEL.

Stress at Elastic Limit. Tons per square inch.	Maximum Stress. Tons per square inch.	Extension per cent. on 5in.	Reduction in Area per cent.
27·55	51·10	22·7	41·05
27·50	46·55	23·0	43·95
21·20	45·20	13·5	17·90
21·95	43·10	24·5	39·05
19·65	32·45	4·1	5·00
19·80	35·90	9·2	10·40
20·40	33·55	25·5	53·75
16·85	23·95	6·05	5·70

189. The Strength of Gun Steel.—The treatment and strength of the steel used in the manufacture of ordnance has been fully discussed in a paper by Col. Maitland, R.A.§ The paper is accompanied by a large number of test results, some of which are quoted below. The material bearing the name of gun steel is a ductile metal having a tensiie strength of about 30 tons per square inch in its

§ "The Treatment of Gun Steel," Min. Proc. Inst. C.E., vol. lxxxix.
‡ From Min. Proc. Inst. C.E., vol. xcv.

soft state, and about 45 tons per square inch when it has been hardened in oil. This hardening is effected by immersing the steel at a temperature of 1,450° Fah. in a bath of cool oil. Col. Maitland further states that the chemical composition is about 0·25 to 0·50 per cent. of carbon and 0·80 to 0·05 per cent. of manganese. The following figures comprise the chief test results quoted by Col. Maitland :—

TENSILE STRENGTH OF GUN STEEL.

Description of Material.	Elastic Limit. Tons per sq. inch.	Maximum Strength. Tons per sq. inch.	Elongation per cent. on 2in.
Sample from ingot, cut longitudinally, heated once, but not worked	15·40	31·80	19·50
Piece cut longitudinally from ingot, heated twice, and worked once...	14·60	32·00	26·50
Piece heated four times, worked three times, cut longitudinally ...	24·20	32·60	31·0
Piece cut from gun tube, across grain, and soft	16·00	34·60	11·0
Piece cut from gun tube, across grain, oil-hardened.................	28·20	45·20	10·0
Cut from gun tube, with grain, soft	15·80	35·20	24·0
Cut from gun tube, with grain, oil-hardened	—	52·90	14·0
Cut longitudinally from gun tube, tempered at 1,450°, and boiled in oil at 800°	29·40	46·00	19·5
Cut longitudinally from gun tube, annealed in ashes at 1,000°	27·20	40·40	24·0
Cut circumferentially from gun tube, soft, and unboiled	14·80	33·00	20·0
Cut circumferentially from gun tube, tempered at 1,450°, and unboiled	26·00	41·80	17·0
Cut circumferentially from gun tube, tempered at 1,450°, heated to 1,000°, and annealed	26·00	40·00	23·0
Cut circumferentially from gun tube, tempered at 1,450°, not boiled, but re-tempered at 1,450°	30·00	44·00	10·0

The above figures are not average results, but are selected from a large number of those quoted.

190. Tests of Fluid-compressed Steel.—Some interesting results are given by Mr. W. H. Greenwood || as to the relative strength of steel from fluid-compressed ingots, and steel from ingots having the same composition and treatment but not having been compressed. The results show, what is always held to be the case, that in all respects the fluid-compressed steel is better than that from the uncompressed ingots.

TABLE I.—COMPARISON OF THE AVERAGES OF LONGITUDINAL TESTS OF STRENGTH FROM AN UNCOMPRESSED INGOT, WITH THE CORRESPONDING TESTS FROM PRESSED INGOTS.

Material.	Elastic Limit. Tons per sq. inch.	Breaking Tensile Stress. Tons per sq. inch.	Reduction of Area per cent.	Extension per cent. on 4in.
Longitudinal Pieces.				
Uncompressed ingot (35 specimens) ...	11·11	29·18	4·11	8·76
Pressed ingot (49 specimens)	11·45	29·53	7·90	12·51
Diametrical Pieces.				
Unpressed ingot (35 pieces)	11·43	28·64	3·61	7·91
Pressed ingot (49 pieces)	12·38	30·07	7·57	12·74

In addition to the above results of tests of the metal as taken direct from the ingot without it having undergone any subsequent treatment, Mr. Greenwood quotes the following, obtained from fluid-compressed steel which has undergone the operations of forging and hardening:—

|| Min. Proc. Inst. C.E., vol. xcviii.

TABLE II.—TESTS OF PIECES TAKEN FROM FLUID-COMPRESSED STEEL FORGINGS.

Material.	Elastic Limit. Tons per square inch.	Ultimate Strength. Tons per square inch.	Elongation percentage on inches.
Gun tube, forged and annealed	27·59	—	—
	28·53	49·56	18·3 on 4in.
Gun tube, forged & annealed	29·46	53·58	17·9 ,,
,, ,, ,,	24·77	46·89	20·2 ,,
Hoops for 11in. guns.........	18·75	34·83	17·2 ,,
,, ,, ,, ...	16·74	30·81	18·9 ,,
Gun tube, tempered in oil...	27·46	53·57	18·0 ,,
Shell metal, unhardened......	35·82	61·4	8·9 ,,
,, in soft state.....	4·98	33·04	60·88 on 5in.
Same metal, after being hardened and fired from gun, from nose....................	66·08	84·46	4·7 on $\frac{3}{97}$in.
Same metal, nearer the rear	52·24	79·03	6·0 on $\frac{4}{17}$in.
,, ,, at rear..........	46·86	71·00	7·6 on $\frac{4}{9}$in.

In the last-mentioned tests of shell steel the metal was all taken from the same ingot. The first set of results are the average of three test pieces forged from the ingot and left in the soft state, while the last three sets of figures are from the metal of a shell which has been forged, turned, bored, and hardened in the usual way, and then fired at an armour plate, from which it rebounded.

191. **Strength of Manganese Steel.**—The alloy of iron and manganese with a small percentage of carbon, commonly called manganese steel, possesses strength properties which render its use important for very many purposes. Steel containing only small percentages of manganese up to about 1 per cent. are not affected to any noticeable extent by the proporton of manganese present. When the percentage is increased gradually up to about 8 per cent. the ultimate strength of the metal is impaired. But beyond this, up to about 18 per cent., the increase of manganese is accompanied by an increase of strength,

and if the quantity is still further increased beyond this a diminution of strength results. It will be seen from the following figures that with a percentage of manganese of about 14 the steel possesses self-hardening properties, hardening when simply heated and allowed to cool in air. Cooling in oil and water still further hardens the metal.

In a tensile test of manganese steel it is noticed that there is no very well-marked yield point; but the most remarkable feature is the almost entire absence of local contraction, the bar elongating over the whole length uniformly up to the point of fracture, indicating great uniformity in the molecular structure of the material.

The following figures, taken from Mr. Hadfield's ¶ paper on "Manganese Steel," give some indication of the influence of manganese in various proportions on the strength of the steel.

In table I. are given results of tests of specimens of manganese steel having different percentages of manganese present. Tables II. and III. comprise results of tests of Hadfield's ordinary steel. These latter are quoted for comparative purposes.

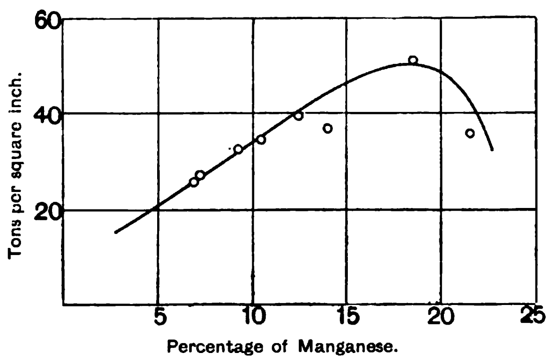


FIG. 180.—SHOWING THE EFFECT OF MANGANESE UPON THE ULTIMATE STRENGTH OF STEEL.

The diagram on Fig. 180 shows graphically the effects on the strength properties of the steel of varying percentages of manganese.

¶ "Manganese Steel," Min. Proc. I.C.E., vol. xciii.

Table I.—Tests of Hadfield's Manganese Steel.

Analysis. Per cent. C.	Mn.	Treatment.	Breaking Load per sq. inch on Original Area. Tons.	Elongation. per cent on 8in.	Reduction in Area per cent.	Appearance of Fracture.
0·20	0·83	Tested as rolled ...	33·5	31·49	45·74	Good
0·40	3·89	Tested as rolled ...	38·0	0·5	...	Granular
0·52	6·95	Forged into test bar and no further treatment.........	25·43	1·50	...	Close
		Heated white hot in cooled air......	21·07	2·34	...	Coarse and granular
		Heated white hot in oil	18·76	1·56	...	Very coarse and bright
		Heated white hot in water	23·25	1·56	...	Coarse and granular
0·47	7·22	Forged into test bar and no further treatment.........	27·44	1·56	...	Fine grain
		Heated as above and cooled in air	26·66	4·68	...	Coarser grain
		Heated as above and cooled in oil	24·89	3·12	...	Open grain
		Heated as above and cooled in water..............	24·63	1·56	...	Rather finer
...	7·50	Tested as rolled ...	38·75	4·3	8·8	Granular
0·50	7·90	Heated as above and cooled in air	28·35	7·81	...	Coarse and granular
		Heated as above and cooled in oil	29·61	7·03	...	Coarse and granular
...	9·20	Tested as rolled ...	40·0	6·1	10·4	Granular
0·61	9·37	Forged into test bar and no further treatment.........	32·59	5·46	...	Granular
		Heated as above and cooled in air	37·706	15·62	...	Coarse and granular
		Heated as above and cooled in oil	38·20	14·84	...	Coarse and granular
		Heated as above and cooled in water..............	38·87	14·84	...	Finer

Tests of Hadfield's Manganese Steel (*Continued*).

Analysis. Per cent. C.	Mn.	Treatment.	Breaking Load per sq. inch on Original Area. Tons.	Elongation per cent. on 8in.	Reduction in Area per cent.	Appearance of Fracture.
1·10	12·60	Forged into test bar and no further treatment..... ...	39·27	2·34	...	Close grain
		Heated as above and cooled in air	37·07	10·93	...	Coarse and granular
		Heated as above and cooled in oil	50·25	28·12	...	Partly fibrous
		Heated as above and cooled in water..............	53·91	27·34	...	Partly fibrous
1·10	12·60	Tested as rolled ...	42·0	3·1	3·6	Granular
0·85	13·75	Heated to high heat and then cooled in water	63·47	45·3	...	...
0·85	13·75	No 19G hard drawn wire	110·7, 107·9, 103·8	This was slightly softened in soldering to the holder.		...
0·85	14·01	Forged into test bar and no further treatment.........	33·43	1·56	...	Slightly defective. Fine grain
		Heated as above and cooled in air	47·90	14·06	...	Granular, fine grain
		Heated as above and cooled in oil	55·04	26·56	...	Fibrous
		Heated as above and cooled in water..............	67·13	44·44	...	Fibrous
1·54	18·4	Forged into test bar and no further treatment.........	51·245	0·78	...	...
		Heated as above and cooled in air	38·973	0·78	...	...
		Heated as above and cooled in water..............	53·249	10·1	...	...
2·10	21·69	Forged into test bar and no further treatment.........	35·97	8·59	...	Fine. Nearly 22 per cent. Mn and 2 per cent. C, yet forgeable
		Heated as above and cooled in air	33·67	11·71	...	
		Heated as above and cooled in oil	33·28	10·93	...	

HADFIELD'S UNHAMMERED STEEL CASTINGS.

Number.	Breaking Load in tons per square inch on Original Area.	Elongation per cent. on 2in.	Reduction per cent. on Area.
1	32·50	29·00	40·42
2	32·50	27·90	33·44
3	34·50	27·77	35·20
4	32·00	26·85	30·98
5	40·00	19·00	20·00
6	45·00	15·00	18·00
7	52·00	4·00	6·35
8	56·80	4·00	5·50
9	64·00	6·00	8·00

HADFIELD'S FORGED CAST STEEL.

Number.	Breaking Load in tons per square inch on Original Area.	Elongation per cent. on 2in.	Reduction per cent. on Area.
1	26·50	40·30	62·76
2	33·50	31·49	45·74
3	46·50	27·02	42·04
4	53·00	25·61	32·00
5	68·50	11·75	21·06
6	75·00	10·00	16·54
7	84·00	11·86	17·50
8	104·00	3·40	8·40
9	125·00	0·95	2·24

192. Effects of Working Iron and Steel at a Blue Heat.—In the accompanying table are some results obtained by Mr. Stromeyer from tests of samples of Siemens-Martin steel. It was pointed out by the author of the paper from which these results are taken that it is usually held that steel may be safely worked at a proper red heat or cold, but that the effect of working the steel at a "blue" or, more properly speaking, "black" heat—that is to say, a high temperature which is short of rendering the metal incandescent—gives rise to effects very

deleterious to the metal. It will be seen that the specimens were treated in a great variety of ways:—

* STROMEYER'S TESTS OF STEEL.

Particulars.	Elastic Limit. Tons per square inch. About.	Highest Tensile Strength. Tons per square inch.	Local Elongation per cent.
Siemens-Martin Steel. Medium Hard. 57·7 tons.			
Annealed red hot	19·6	32·5	11·54
Quenched red hot in boiling water	27·2	38·5	5·83
Quenched red hot in cold water	39·1	48·2	1·17
Annealed red hot, bent hot (violet to straw), and flattened	19·6	33·9	16·73
Siemens-Martin Steel. Mild. 28·2 tons.			
Annealed red hot	16·1	26·5	34·72
Quenched red hot in boiling water	22·3	37·0	16·46
Quenched red hot in cold water	23·0	36·5	12·47
Annealed red hot, bent hot (blue to dark straw), and flattened.	18·3	29·9	20·16
Siemens-Martin Steel. Very Mild. 23·4 tons.			
Unprepared	18·3	27·2	24·80
Quenched red hot in cold water	26·3	39·0	19·42
Annealed blue hot, two nights	19·3	27·4	20·61
Bent cold to a 15in. radius and flattened	18·5	28·1	17·98
Bent hot (blue to straw) and flattened	22·8	29·5	29·40

193. Tests of Steel from Crank Axles.—In making tests of this material it is usual to take the specimens from the slabs cut out in forming the cranks: some of the specimens should be cut radially, and others circumferentially or at right angles to the axis of the shaft. One of these specimens is shown in the accompanying figure (181). The specimen is very small, and only allows of measurements being taken on about 2in.

* Min. Proc. Inst. C.E., vol. lxxxiv.

The following are a few results of tests of axle steel given by Mr. Kirkaldy:—

† KIRKALDY'S TESTS OF STEEL FROM LOCOMOTIVE CRANK AXLES.

Manufactured by	No. of Tests.	Elastic Limit Stress. Tons per square inch.	Ultimate Strength. Tons per square inch.	Percentage Extension on 5in.	Reduction of Area per cent.
Vickers, Sons, & Co.	82	10·74	25·85	24·0	32·9
Vickers, Sons, & Co.	78	10·50	24·65	25·9	32·7
Vickers, Sons, & Co.	47	13·32	27·80	34·2	51·5
Krupp	43	13·15	27·60	32·3	47·7
Krupp	34	14·54	30·00	25·9	46·8

The above figures represent the mean results of the number of tests made, and may be taken as typical.

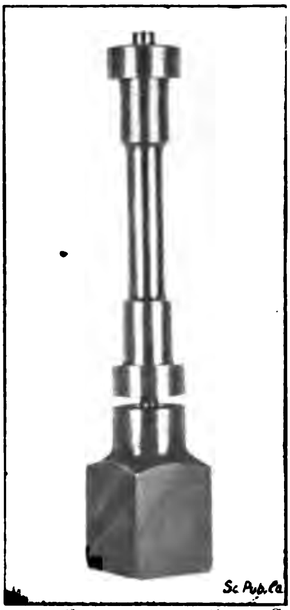


FIG. 181.—TENSION SPECIMEN FROM STEEL CRANK AXLE.

† Abridged from Kirkaldy's "Strength and Properties of Materials."

194. Nickel Steel.—A most valuable alloy is obtained by adding a small portion of pure nickel to a low carbon steel. It is found that up to a certain point the presence of nickel increases the ultimate tensile strength of the metal, and, still more, the elastic strength.

The following figures, given by the Bethlehem Steel Company, shows very clearly the effect of nickel on iron containing a small percentage of carbon:—

STRENGTH OF NICKEL CARBON-IRON ALLOYS.

Percentage. Nickel.	Percentage. Carbon.	Elastic Limit. Tons per square inch.	Ultimate Strength. Tons per square inch.	Elongation per cent.	Reduction in Area per cent.
	0·20	12·50	24·50	34	60
3·50	0·20	21·20	38·00	26	55
	0·30	16·50	33·50	30	50
3·50	0·30	26·80	42·50	22	48
	0·40	19·20	38·00	25	45
3·50	0·40	32·10	49·10	18	40
	0·50	21·40	42·40	21	40
3·50	0·50	38·00	55·80	13	32

Mr. Browne states that it may be taken that, compared with simple steels having the same tensile strength, a 3 per cent. nickel steel will have 20 to 30 per cent. greater elongation; while, compared with simple steels of the same carbon percentage, a nickel steel will have about 40 per cent. greater tensile strength.

Where nickel is alloyed with iron almost pure, and containing little or no carbon, the increase of nickel increases the tensile strength, both ultimate and elastic, but especially the latter, until a percentage of nickel of about 8 is reached; on further increase of nickel the strength diminishes up to about 60 per cent., when a small increase again takes place.

It has been stated that the most remarkable effect which the presence of nickel produces is to increase the ratio of elastic limit to ultimate strength. This is shown in the following table taken from Rudeloff's experiments :—

EFFECT OF NICKEL ON THE RATIO OF ELASTIC LIMIT TO ULTIMATE STRENGTH.

Nickel. Per cent.	Ratio of Elastic to Ultimate. Per cent.
0	45
1	49
2	55
3	59
4	66
5	73
8	79

In the above alloys the nickel was added to a steel very low in carbon. This is shown graphically in the following diagram, Fig. 182 :—

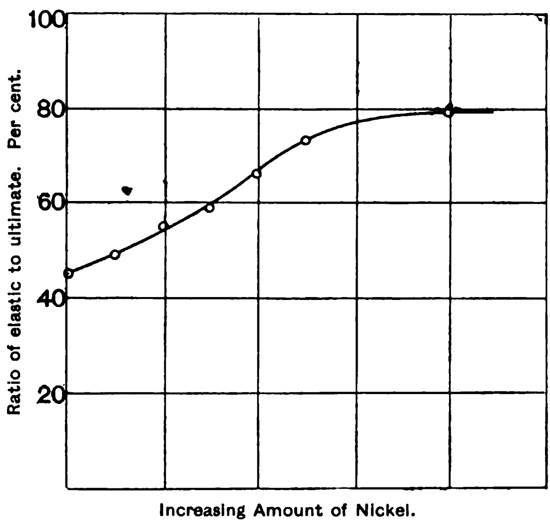


FIG. 182.—SHOWING EFFECT OF NICKEL ON THE STRENGTH OF STEEL

195. **The Compressive Strength** of low carbon steel is effected in the same way as is the tensile, an increase of nickel meaning an increase of compressive strength, the maximum being reached at about 16 per cent., beyond which point the strength diminishes. Mr. Hadfield gives the compressive elastic limit for a steel having 11·39 per cent. nickel as 100 tons per square inch.

196. **In Shear** also the same result is found to take place, the maximum strength being reached with about 16 per cent. nickel, the shearing strength at this point being about 43 tons per square inch.

‡Mr. Browne gives the result of a test of a nickel steel tyre, the steel being made at the Parkhead Forge in Glasgow. The steel contained 0·18 per cent. carbon and 3 per cent. nickel, and yielded results of 24·50 tons per square inch elastic limit in tension; 38·80 tons per square inch ultimate strength; 28·7 per cent. elongation; and 46 per cent reduction in area.

Nickel steel appears to possess excellent qualities for the purposes for which tool steels are used. In this case the percentage of carbon is raised also. It hardens and tempers well, and retains more of its ductile properties under the hardening treatment than do ordinary steels, and attains a remarkably high tensile strength when hardened.

Another valuable property of nickel steel is its incorrodibility. Tests would appear to show that this alloy resists the attacks of damp atmosphere and corrosive fumes to a remarkable degree.

197. **Elastic Moduli for Steel.**—The modulus of elasticity for steel in tension and compression varies from 26,000,000lbs. to about 31,000,000lbs. per square inch, the more usual values being between 28,000,000lbs. and 30,000,000lbs. per square inch. For the same material the modulus in tension is, as a rule, slightly higher than that in compression. That the modulus of elasticity does

‡ From Browne, American Institute of Mining Engineers, California Meeting, 1900.

not necessarily vary to any great extent with the other properties, both chemical and mechanical, is shown by the following figures, quoted by Johnson :—

§ MODULUS OF ELASTICITY OF STEELS HAVING DIFFERENT PERCENTAGES OF CARBON. (MARSHALL.)

Number of Heats and Tests.	Average percentage of Carbon.	Elastic Modulus. Tons per square inch.	Kind of Steel Tested.
33	0·09	13,360	Bessemer
8	0·11	13,400	Open hearth
107	0·24	13,390	,,
89	0·34	13,240	Bessemer
25	0·72	13,360	Open hearth

Other tests by Mr. Marshall give the average elastic modulus of nine bars of the same material as 13,710 tons per square inch in tension, and the average result of nine bars of the same material in compression as 13,150 tons per square inch; corresponding results from eight bars of spring steel are respectively 13,170 and 13,070 tons per square inch. The modulus is thus seen to be higher in tension than in compression.

RICKETTS' TESTS OF THE ELASTIC MODULUS OF STEEL.

Kind of Steel.	Elastic Modulus. Tons per square inch. Tension E_T.	Elastic Modulus. Tons per square inch. Compression E_C.	Ratio of E_T to E_C.
Open hearth steel rivet.	13,600	13,160	1·033
,, ,,	13,630	13,080	1·043
,, ,,	13,660	13,100	1·043
,, ,,	13,610	13,110	1·044
,, ,,	13,140	13,100	1·035
Bessemer steel	13,110	12,830	1·014
,,	13,610	13,380	1·020
,,	13,350	13,000	1·027
,,	11,900	13,100	1·109

§ From experiments by Marshall, Trans. Am. Soc. C.E., vol. xvii.

The above figures, taken from a paper by Mr. Ricketts in the American Society Civil Engineers, in 1887, are from the results of a large number of tests of samples of steel having various percentages of carbon. For each set the figures higher up the list contain the smaller percentage of carbon. It will again be noticed that the modulus is in all cases higher in tension than in compression.

198. Modulus of Rigidity for Steel.—The following table contains values of the modulus of direct elasticity and the modulus of rigidity, taken from various sources:

VALUES FOR THE MODULUS OF DIRECT ELASTICITY AND MODULUS OF RIGIDITY.

Material.	Modulus of Elasticity E. Tension. Tons per sq. inch.	Compression. Tons per sq. inch.	Bending. Tons per sq. inch.	Modulus of Rigidity. G. Tons per sq. inch.	Ratio. $\frac{G}{E}$	Authority.
Bessemer steel from Ternitz...	14,740	{14,800 / 14,500}	13,960	5,625	0·388	Bauschinger, from Unwin.
Siemens-Martin steel from Neuberg-Mariazell.	13,380	13,405	13,430	5,315	0·396	
Bessemer steel ...	13,160	—	—	5,750	0·437	Platt and Hayward.
Crucible steel ...	13,280	—	—	6,100	0·538	
Siemens-Martin steel	13,000	—	—	5,980	0·460	
Landore rivet steel	12,900	—	—	5,830	0·452	
Cast steel	13,560	—	—	5,820	0·430	
Ordinary mild steel	13,870	—	—	—	—	Author.

199. Determination of the Elastic Modulus by a Committee of the British Association.—These tests were primarily undertaken for the purpose of comparing the behaviour of the different kinds of extensometers in use, and have already been mentioned (p. 125). The results of tests on six different bars of steel are given. The bars tested were as follows :—

Flat bars, A and B, of ordinary mild steel.

Cylindrical bars, E and F, of specially strong steel, rolled for the committee by the Blænavon Company.

Cylindrical bars, K and L, of the same material as the above. Seven different extensometers were used, with the following results :—

TENSION MODULUS OF ELASTICITY OF STEEL BARS.

Bar.	Number of Observers.	Mean Elastic Modulus, in tons per square inch, of all results of all observers.	
A	4	13,182	13,193
B	4	13,203	
E	4	13,225	13,249
F	3	13,273	
K	4	13,274	13,245
L	4	13,215	

200. Strength of Steel in Shear and Torsion.—The ratio of the ultimate shearing strength of steel to its strength in tension has already been referred to (p. 167), and some results collected from various sources are there given. Some of these are repeated in the following table, with the addition of others. The ultimate shearing strength, as calculated from the breaking moment in torsion tests, is also quoted in some cases. Two values of this *coefficient of torsional strength* have been calculated. The first is calculated by the usual torsion formula, which assumes elasticity up to the point of fracture, the formula being

$$f_T = \frac{2}{\pi}\frac{T}{R^3}$$

The second formula assumes equality of stress over the cross section of the shaft at the point of fracture, and is

$$f_T = \frac{3}{2\pi}\frac{T}{R^3}$$

The results in the table show that the conditions assumed in the second formula are those which actually obtain, the coefficients being in most cases very near the shearing strengths as obtained from direct shearing experiments. The figures in brackets are not given by the authorities named, but have been calculated by the author from the published results.

In the author's torsion tests the results are the averages of five tests of solid shafts and five hollow shafts :—

THE STRENGTH OF STEEL IN SHEAR AND TORSION.

Material.	Tensile Stress. f_t	Direct Shearing Stress. f_s	Ratio. $\frac{f_s}{f_t}$	Coefficient of Torsional Strength. $f_T = \frac{2T}{\pi R^3}$	Coefficient of Torsional Strength. $f_T = \frac{3T}{2\pi R^3}$	Authority.
	Tons per sq. inch.	Tons per sq. inch.		Tons per sq. inch.	Tons per sq. inch.	
Bessemer steel—Turton Bros.—(mean of 3) ...	52·20	35·21	0·68	44·64	(35·50)	Platt and Hayward, Min. Proc. I.C.E., vol. xc.
Crucible steel—Sir J. Brown & Co.—(mean of 3)	52·16	33·30	0·64	42·30	(31·70)	
Landore rivet steel (mean of 3)	28·40	23·00	0·81	29·85	(22·40)	
Cast steel—Sir J. Brown & Co.—(mean of 3) ...	38·04	27·6	0·73	34·7	(26·00)	
Siemens - Martin steel (mean of 3)	25·75	21·05	0·82	28·13	(21·15)	
Ordinary mild steel, solid......	25·95	22·45	0·86	29·09	21·82	Popplewell and Coker, Min. Proc. I.C.E., vol. cxxii.
Ordinary mild steel, hollow...	25·95	22·45	0·86	27·51	23·15	

On Fig. 183 is given a load-strain curve for a shaft specimen of mild steel tested by the author.

201. The Strength of Steel Castings.—Some of the best test results for steel castings are those by ‖ Mr. Abbott, of Messrs. Fairbanks. Mr. Abbott made a very complete series of tests of steel castings in tension, compression, and bending, the castings being made from similar patterns by ten different steel makers in the United States. Mr. Abbott gives the size of his test bars as follows :—

For tension, 1½ins. diam., 10ins. long between the gauge points.

For compression, 2ins. square, 2½ft. long.

For transverse stress, 2ins. square, and 2ft. long.

‖ Min. Proc. Inst. C.E., vol. lxxxiii.

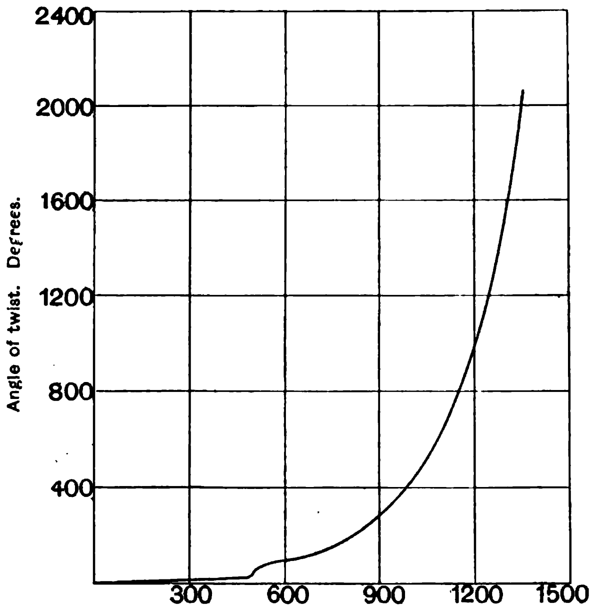


FIG. 183.—LOAD-STRAIN DIAGRAM FOR SHAFT OF MILD STEEL. 5in. long and 0·473in. diam.

The results of the tests on the 10 different metals are set forth in the following table:—

STRENGTH OF STEEL CASTINGS.

No.	Elastic Limit Tension. Tons per sq. inch.	Ultimate Tensile. Tons per sq. inch.	Elongation per cent.	Elastic Limit in Compression Tons per sq. inch.	Elastic Transverse Limit. Pounds per sq. inch.	Ultimate Transverse. Pounds per sq. inch.
1	12·90	19·45	6·00	15·61	6,000	8,000
2	11·44	16·47	0·40	13·97	2,500	3,870
2	11·45	18·85	0·80	—	2,600	3,950
3	10·30	19·75	6·00	10·90	3,000	4,181
4	9·54	17·10	10·00	11·50	3,950	5,720
6	13·90	20·65	2·00	13·25	4,000	6,259
7	16·00	25·30	10·00	16·10	4,000	5,480
9	15·85	23·30	9·00	12·05	4,000	6,810
9A	17·10	28·1	29·00	—	—	—
9A	17·10	28·00	20·5	—	—	—
10	7·82	14·35	8·00	9·14	2,500	4,010

Mr. Abbott further gives the average modulus of elasticity for all the bars tested as 10,900 tons per square inch. It will be seen that the elastic limit in compression is not very different from the elastic limit in tension.

Results by other investigators accord fairly well with those just given, although in some cases the tensile strength gets up to 45 tons per square inch. Mr. Hill's results show that, although the tensile strength is not greatly affected by annealing, the ductility, as shown by the extension and reduction, is greatly increased.

Other Special Steels.—Tungsten, when added to steel in the proportion of about 8 per cent., produces a metal of great natural hardness, which is not increased by quenching, nor diminished by annealing. Tungsten steel requires great care in working.

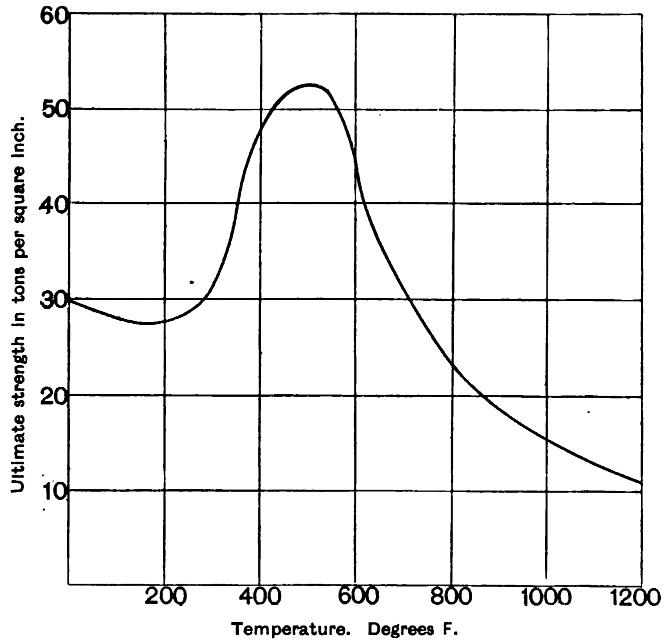


FIG. 184.—EFFECT OF TEMPERATURE ON THE STRENGTH OF HIGH CARBON STEEL. (JOHNSON.)

Aluminium, added to good-class wrought iron, enables the metal to be formed into castings, called Mitis castings,

having the properties of wrought iron, except that they are homogeneous and without the appearance of fibre. These give a tensile strength of about 27 tons per square inch.

When added to steel, aluminium makes it possible to produce much sounder castings that without it.

The Effect of Temperature on the strength of steel is shown graphically on Fig. 184.

CAST IRON.

202. The chief mechanical properties of cast iron, as distinguished from wrought iron and steel, are its non-malleability at all temperatures, brittleness, fusibility, high compressive strength, and low tensile strength.

The chemical constituents of this material are chemically pure iron, carbon (either combined or mechanically mixed), silicon, sulphur, phosphorus, manganese, and arsenic. Of these, the sulphur, phosphorus, arsenic, and silicon remain as impurities, which are not eliminated during the processes of manufacture; the carbon and manganese remain as important ingredients, whose presence largely determines the mechanical qualities of the iron.

The percentage of carbon present in cast iron, either combined or mixed, varies from 1·5 to 6·0 per cent. according to the process by which the iron has been produced. It is customary for ironfounders not to make the castings from one kind of pig only, but to mix two or more kinds in varying proportions, so as to produce a finished material having the necessary degree of hardness, toughness, or tensile strength, as the case may be. The following table gives the constituents of eight samples of pig from different districts :—

¶ Composition of Cast Iron of Various Grades.

	Grey Cinder Pig.	Common White Pig.	Mottled Iron.	Best Mine Pig.	Foundry Pig.	Grey.	Mottled	White
Iron	93·55	95·27	93·29	94·56	93·53	90·24	89·39	89·86
Combined carbon	2·80	2·42	2·78	0·04	—	1·82	1·79	2·46
Graphite			1·99	3·10	3·44	2·64	1·11	0·87
Silicon	1·85	0·36	0·71	2·16	1·13	3·06	2·17	1·12
Sulphur	0·14	0·87	trace	0·11	0·03	1·14	1·48	2·52
Phosphorus	1·66	1·08	1·23	0·63	1·24	0·93	1·17	0·91
Manganese	—	—	—	0·50	0·43	0·83	0·60	2·72

203. Tensile Strength of Cast Iron.—This varies from seven to 15 tons per square inch in extreme cases, but more usually from eight to 11 tons.

In the following table are quoted tensile strengths of cast iron given by different authorities :—

Tensile Strength of Cast Iron.

No. of Tests from which the averages have been taken.	Tensile Strength. Tons per square inch.	Authority.
—	11·82	Secundo and Robinson.
14	11·10	,, ,,
6	13·50	Major Wade.
4	10·50	,, ,,
9	10·10	Kirkaldy.
10	12·50	,,
10	11·10	,,
15	10·30	,,
13	9·70	,,
—	7·37	Hodgkinson and Fairbairn.
81	6·83	,, ,,
2	9·74	Popplewell and Coker.
2	7·03	Popplewell.
850	9·45	Anderson.

¶ From "Casting and Founding," Spretson.

Thurston, in his book on "Iron and Steel," gives the following values for the tensile strength of cast iron under various conditions :—

TENSILE STRENGTH OF CAST IRON. (THURSTON.)

Kind of Iron, and Conditions of Preparation.	Tensile Strength in tons per square inch.
Ordinary Conditions.	
Good pig iron	8·93
Tough cast iron	11·15
Hard „	13·37
Good tough gun iron	13·37
Remelted cast iron.	
First melting	6·26
Second „	10·25
Third „	13·50
Fourth „	15·96
Effect of varying time of fusion.	
Fused for ½ hour	7·97
„ 1 „	8·99
„ 1½ „	10·90
„ 2 „	15·70

Load-strain diagrams for cast iron in tension and compression are shown on Fig. 185. The compression curve is only partial.

204. Compressive Strength of Cast Iron.—The strength of cast iron in compression varies from 25 to 85 tons per square inch.

Several important series of experiments have been carried out by the American Foundrymen's Association, with a view to determining a set of standard specifications for cast iron. The first set of these clearly show that specimens cast in small moulds give a higher result per square inch than do larger specimens of the same material mixture. In this series the crushing specimens were in the form of cubes.

In the third set the iron used was of a very fluid nature, such as is suitable for light machinery castings, and having a composition of 3·52 per cent. free carbon, 0·32 combined carbon, 2·04 silicon, 0·39 manganese, 0·58 phosphorus, and 0·044 sulphur.

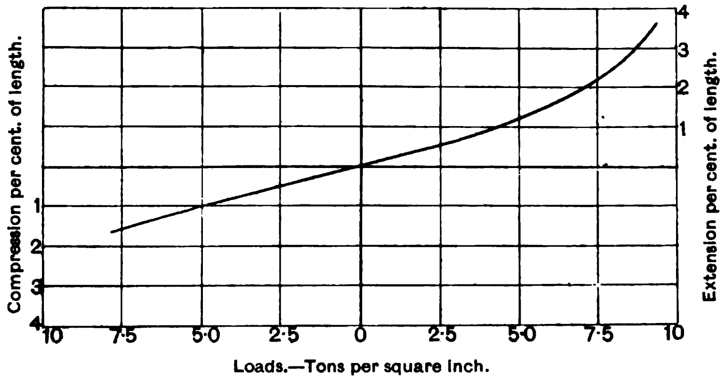


FIG. 185.—LOAD-STRAIN CURVE FOR CAST IRON IN TENSION AND COMPRESSION.

The specimens were ½in. cubes, cut from different parts of bars of larger section. The results were as follow:—

COMPRESSION TESTS OF ½IN. CUBES OF LIGHT MACHINERY IRON.

Cross Section of Bar from which Cubes were cut.	Crushing Strength, in tons per square inch, for Cube.				
	Middle half-inch.	First half-inch.	Second half-inch.	Third half-inch.	Fourth half-inch.
Inches.					
½ × ½	69·0	—	—	—	—
1 × 1	44·5	49·8	—	—	—
1½ × 1½	37·0	39·4	37·0	—	—
2 × 2	32·2	38·9	34·6	—	—
2½ × 2½	31·9	35·4	32·3	31·9	—
3 × 3	28·6	32·5	30·1	28·7	—
3½ × 3½	28·4	30·5	29·6	28·8	28·4
4 × 4	25·4	29·4	27·4	26·6	25·4

These tests also plainly show that the specimens taken from the bars of small cross section give higher results than those from larger bars.

It is also to be noted that for crushing specimens of equal cross section the shorter pieces may be expected to yield the higher results.

Hodgkinson gives the following values for the compressive strength of cast iron :—

HODGKINSON'S TESTS (From "Rules and Tables," Clark).

Kind of Iron.	Compression Strength. Tons per square inch. Height of Specimen, ¾in.	Height of Specimen, 1½in.
Lowmoor, No. 1	28·81	25·19
„ No. 2	44·43	41·22
Blænavon, No. 1	40·56	35·96
„ No. 2	52·50	45·70
Stirling's iron, 2nd quality.........	55·95	53·30
„ „ 3rd „	70·83	57·98

Stirling's iron is cast iron melted with wrought iron.

205. Cross Breaking Strength of Cast Iron.—The most common test for cast iron is that under a transverse load. This is so, both because the test can easily be carried out with simple appliances, and also because the results given are more likely to be uniform and reliable than those in pure tension. The sizes specified for this test are either 1in. × 1in. × 12in. span, or 2in. deep × 1in. wide × 36in. span, and for the latter dimensions the central load which the bar is specified to stand varies from 25cwts. to 30cwts.

It has already been pointed out that the beam formula for rectangular beams,

$$W = f_b \cdot \frac{2}{3} \cdot \frac{b \cdot d^2}{l},$$

does not hold except in cases where the material is elastic. In the case of cast iron it is found that the maximum stress, as given by the above formula, when calculated from the central breaking load, exceeds to a considerable extent the tensile stress found for the same iron from

tensile tests. This value, as given by bending tests, has been called the *coefficient of bending strength*, and is given by

$$f_b = \frac{W \cdot 3 \cdot l}{b \cdot d^2 \cdot 2}.$$

In the following table are quoted results of tests on rectangular bars of cast iron, showing the values of the coefficient of bending strength for different grades of iron :—

CROSS BREAKING TESTS OF CAST IRON.

Description.	Depth. Inches.	Breadth. Inches.	Span. Inches.	Breaking Load. Tons.	Coefficient Tons per sq. inch. f_b	Authority.
Rectangular. Planed ...	2·93	0·90	20	4·89	18·25	Secundo and Robinson, Min. Proc. I.C.E., vol. lxxxvi.
	2·93	0·90	20	4·76	17·71	
	0·90	2·93	20	1·52	18·82	
	0·90	2·93	20	1·49	18·50	
Rectangular. Mean of 2 ...	1	2	15	1·57	17·68	Secundo. Min. Proc. I.C.E., vol. xcviii.
,, ...	2	1	15	3·01	16·95	
Rectangular.	2	1	36	1·33	17·60	Author.
Rectangular. Mean of a large number	2	1	36	1·26	16·95	Kirkaldy.
Rectangular.	2	1	36	1·67	22·53	Millar, Min. Proc. I.C.E., vol. lviii.
	1	1	36	0·36	19·30	
	1	2	36	0·79	20·80	

In addition to the experimental results given in the above table, Mr. Millar carried out a number of tests, in order to determine the effect upon the strength of the bar, of the condition of the metal in the ladle previous to pouring It was found that where the metal was run at a very high temperature it had a somewhat lower breaking strength than when run at a dull heat ; while, on the other hand, the deflection was slightly higher.

The deflection of a cast-iron beam of the usual proportions (2in. deep by 1in. wide) may be taken very approximately as $\frac{1}{10}$th of an inch for each 1,000lbs. of central load.

The strain of cast iron, of whatever kind, is always made up of an elastic distortion and a small amount of permanent set. On removing the load from a bar the set does not disappear, and if the bar is again loaded in to the same extent it will be found that the total deflection (in the case of a beam) is less than formerly, because the set has been to some extent eliminated; and if the loading is again repeated the total strain will still continue to decrease. Mr. Millar experimented upon this point, and published a number of figures, of which the following may be quoted as representative: A beam of the ordinary dimensions was loaded five times, and finally broke at a load of 3,500lbs. and a deflection of 0·403in. For each loading the same load was applied, viz., 2,800lbs.; and deflections were respectively for the first up to the fifth loading, 0·302in., 0·282in., 0·279in., 0·278in., 0·276in., and 0·273in. A load-strain diagram for a cast-iron beam is given on Fig. 186.

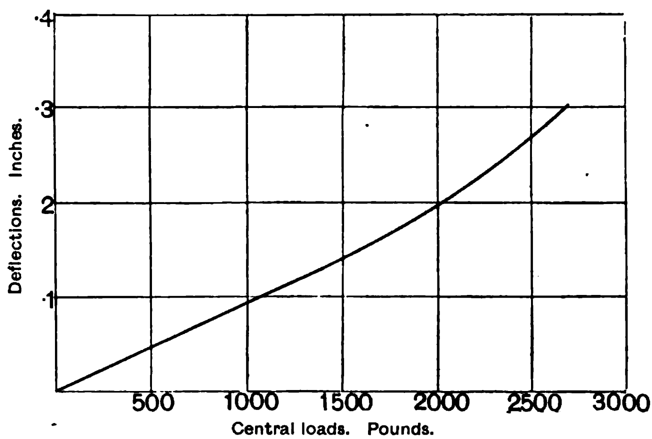


FIG. 186.—LOAD-STRAIN CURVE FOR A CAST-IRON BEAM. 2in. × 1in. × 36in. span.

206. Cast Iron in Shear and Torsion.—The following test results are for cast iron in direct shear and torsion. The testing of cast iron in direct shear is an uncertain process, as it is difficult to entirely eliminate any tendency to bending. The cast-iron shafts tested by Mr. Coker and the author* were both solid and hollow, there

* Min. Proc. Inst. C.E., cxii.

being five of each, and the results quoted are the means of these. The hollow shafts were 0·5in. outside diameter and 0·313in. inside. The solid shafts were of the same nominal strength (that is, 0·473in. diam.), giving a ratio of weight solid to weight of hollow of 1·46 to 1. It will be seen that the solid shafts give the higher results.

The diagram for a cast-iron shaft tested by the author is given on Fig. 187.

Cast Iron in Shear and Torsion.

Description of Test.	Shearing Strength. Tons per sq. inch. f_S	Coefficient of Torsional Strength. Tons per sq. inch. f_T	Ratio. $\frac{f_S}{f_T}$ Per cent.	Modulus of Rigidity. G. Lbs. per sq. inch.	Authority.
Cast iron:— 1 part Darlington, 5 parts best scrap. (Average of 6.) Turned.	5·22	15·9	32·9	7,163,000 Tons per sq. in 3,200	Platt and Hayward. Min. Proc. I.C.E., vol. xc.
Same as above. (Average of 3) Skin on.	4·44	18·1	24·5	7,620,000 Tons per sq. in. 3,410	
1 part Sunderland pig No. 3 3 parts scrap. Turned. (Average of 6.)	5·08	17·1	29·8	6,602,000 Tons per sq. in. 2,950	
Same as above, with skin on. (Average of 5.)	3·92	15·3	25·6	7,050,000 Tons per sq. in. 3,145	
Mixture:— 4 parts Shott's pig, 6 No. 3 Clyde Hæmatite. Solid. Mean of 5.	9·54	14·56	60·55	—	Popplewell and Coker. Min. Proc. I.C.E., vol. cxxii.
Same as above. Mean of 5. Hollow.	9·54	10·38	92·00	-	

207. Modulus of Elasticity for Cast Iron.—The elastic modulus for cast iron, as well as for most of the alloys, is a somewhat variable quantity. It has been pointed out that the deflections of cast-iron beams vary according to the number of times the loads have been applied; and, therefore, it is to be assumed that the value of the modulus calculated from the first loading, will be different from the value obtained after the bar has been half-a-dozen times under the load, because the metal will have taken up the greater part of its permanent set. The modulus also varies with the grade of metal and the conditions of casting. Unwin asserts that there is no true modulus for cast iron, as the set can never be quite eliminated.

Johnson states that the modulus for cast iron varies from 12 to 15,000,000lbs. per square inch.

The following figures give the values as obtained by different experimenters :—

TABLE OF MODULUS OF ELASTICITY FOR CAST IRON.

Description of Test.	Tension Modulus.		Transverse Modulus.		Authority.
	Pounds per square inch.	Tons per square inch.	Pounds per square inch.	Tons per square inch.	
Rectangular Beams (average of 7 tests)	—	—	11,172,000	4,990	Secundo, I.C.E., xcviii.
Tension bar	12,500,000	5,580	—	—	
Rectangular Beams...	—	—	13,800,000	6,160	Secundo and Robinson, Prc. I.C.E. lxxxvi.
Tension bars (10) ...	14,680,000	6,280	—	—	
	15,000,000 (compression)	6,700	—	—	
Tension bars (2) ...	11,600,000	5,180	—	—	Author.
Tension bars (3) ...	15,560,000	6,950	—	—	Platt and Hayward.
Nine Long Tension Bars (mean)	12,510,000	5,583	—	—	Hodgkinson.
The same with small amount of permanent set eliminated	13,570,000	6,054	—	—	Hodgkinson.

208. The Effect of Temperature on the Strength of Cast Iron.—No great difference is observable in the tensile strength of cast iron as the temperature is increased, until a temperature of about 900° Fah. is reached. Up to this

point there is a very slight increase of strength, but afterwards, as the temperature is still further increased, the strength continually diminishes, being only about 50 per cent. of its strength at the normal temperature at 1,100°, and falling to 25 per cent. at 1,400°.

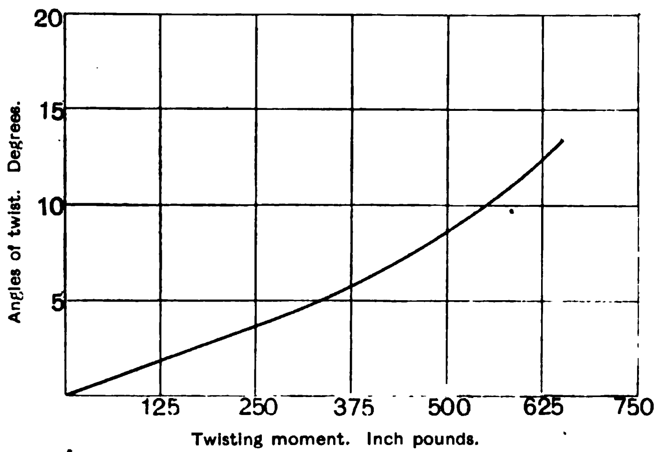


FIG. 187.—LOAD-STRAIN CURVE FOR A CAST-IRON TORSION SPECIMEN. 5in. long and 0·473in. diam.

209. The Strength of Cast Iron Thick Cylinders.—In thin cylinders—such as steel or wrought-iron pipes, and steam boilers—where the thickness is small compared with the diameter, the tensile stress is taken as being sensibly constant across the whole thickness, and the calculation of their strength becomes simple; but in thick cylinders, where the thickness forms a large proportion of the external diameter, the case is different. The tensile stress in the metal, caused by the uniform pressure of an internal fluid, varies continuously from the inner to the outer surface, being greatest at the inner surface. The relation between the dimensions of the cylinder, the internal pressure, and the maximum tensile stress in the material is given by Lamé's formula, which is deduced purely by mathematical reasoning, on the assumption that the material remains perfectly elastic. The equation is the following:—

$$\frac{p}{f} = \frac{R^2 - r^2}{R^2 + r^2}$$

where p is the internal pressure of the fluid,

f is the maximum tensile stress in the material, caused by this pressure,

R is the external radius of the cylinder,

and r is the internal radius.

The relation expressed by this equation is chiefly of use in connection with the design of hydraulic cylinders and pipes, and ordnance.

Tests of specimen thick cylinders are sometimes made in ordinary testing machines by filling them with a fluid

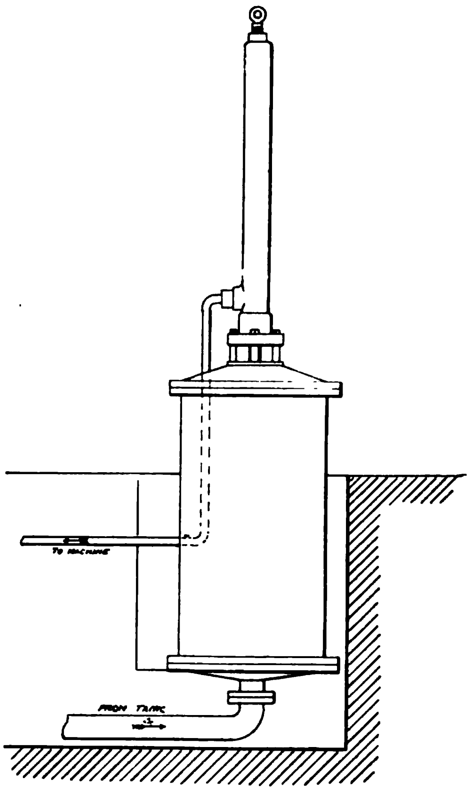


FIG. 188.—ARRANGEMENT OF INTENSIFIER IN THE OWENS COLLEGE TESTING MACHINE.

substance and forcing a ram in by placing the cylinder between the compression plates of the testing machine.

Prof. Thurston quotes some results of tests on thick cylinders of cast iron for guns made at Watertown Arsenal. The cylinders, of which there were nine, were 11in. external, 3·3in. internal diameter, and 22½in. long. Each cylinder was burst by first filling it with wax and then forcing in a ram by means of an ordinary testing machine. The results show that the pressure required to burst the cylinders was in all cases slightly lower than that given by any of the usual formulas for thick cylinders.

210. Model Thick Cylinder Tested by the Author.†—In 1889 the author made a test of a small thick cylinder under the following circumstances. Soon after the completion of the 100-ton Buckton testing machine for the Whitworth Engineering Laboratory at the Owens College, the ram cylinder of the hydraulic intensifier (shown on Fig. 188) was burst, as it was thought, by the impulsive action of the water from the pressure tank upon the piston. Owing to the sudden stoppage of the column of water coming from the tank, the pressure was greatly above that due to the head alone, and to this is attributed the fracture of the ram cylinder, rather than to any inherent defect in the cylinder itself. The broken cylinder was replaced by a new one of cast steel, with perfectly satisfactory results; and, at the suggestion of Prof. Osborne Reynolds, under whose direction the tests were carried out, the author cut from the walls of the fractured cylinder a model cylinder, one-eighth the size of the original one, and similar in all important points. An elevation and section of this model are shown on Fig. 189. It will be seen that the top of the cylinder is closed by a screw plug and a packing of leather discs; the lower end was provided with a stuffing box, packed with leather washers, and allowing the passage of a ram, also one-eighth the size of its full-sized counterpart. In order to reproduce, as far as possible, the conditions obtaining when the large cylinder was burst, the model was placed for testing between the compression plates of the machine, with its upper end quite free and the shoulder at the lower extremity resting on the end of a piece of 1¼in. steam pipe.

† See Owens College Calendar for 1890-91.

In order to carry out the test, the cylinder was filled with water, the ram inserted, and the packings all made as water-tight as possible.

The cylinder was then placed between the compression plates of the testing machine, as shown on Fig. 189. The load on the ram was increased until it reached 0·650 tons, when the cylinder burst with a longitudinal fracture about 4in. in length; this fracture is indicated on the left-hand view on Fig. 189.

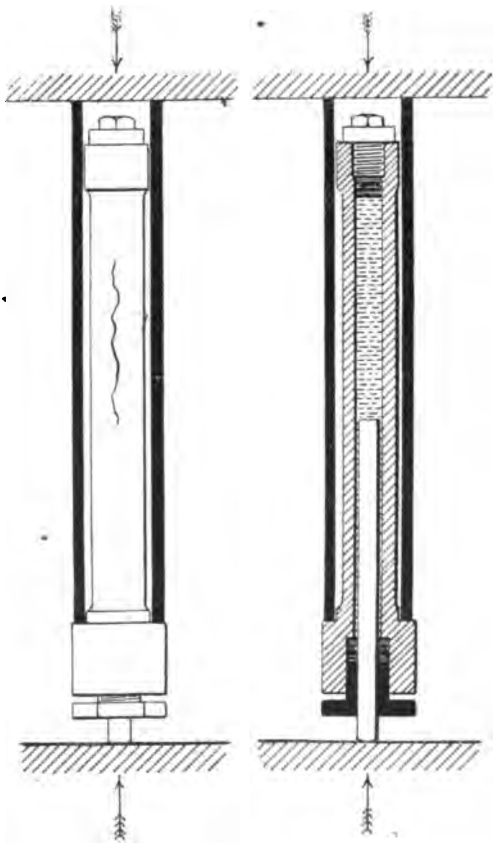


FIG. 189.—ELEVATION AND SECTION OF CAST-IRON TEST CYLINDER.

In addition to the model cylinder, two tension test pieces were cut from the broken cylinder. These were

tested, and broke at 6·95 tons and 7·29 tons per square inch respectively, or with a mean tensile strength of 7·12 tons per square inch.

Now, using Lamé's formula (given above) to calculate the maximum tensile stress in the model cylinder at the bursting load, the following are the data required :—

External radius of cylinder $= R = 0{\cdot}515$in.
Internal radius of cylinder $= r = 0{\cdot}265$in.
Diameter of ram $= 0{\cdot}445$in.
Sectional area of ram $= 0{\cdot}155$ sq. in.

The bursting pressure in tons per square inch will be

$$p = \frac{0{\cdot}65}{0{\cdot}155} = 4{\cdot}193 \text{ tons per square inch.}$$

The maximum stress, as calculated from the bursting pressure, is

$$f = p \cdot \frac{R^2 + r^2}{R^2 - r^2}$$

$$= 4{\cdot}193 \cdot \frac{(0{\cdot}515)^2 + (0{\cdot}265)^2}{(0{\cdot}515)^2 - (0{\cdot}265)^2}$$

$$= 4{\cdot}193 \cdot \frac{0{\cdot}335}{0{\cdot}195}$$

$$= 7{\cdot}203 \text{ tons per square inch.}$$

This result lies between the two results of the tensile tests given above, so that it may be assumed that in this instance the actual results accord very well with the theoretical values deduced from Lamé's formula.

Proceeding on similar lines for the original cylinders, it was found that the maximum stress in the metal, due to the greatest static pressure (5,400lbs. per square inch), would be only about four tons per square inch, whereas the tensile strength of the metal was found to be over seven tons per square inch ; so that it must be supposed that the increased pressure was due to inertia effects of the water.

The static head was derived from a tank placed in the college tower.

MALLEABLE CAST IRON.

211. This term is usually applied to cast iron which has been subjected to an oxidising process after it has been cast into the required shape. This is effected by surrounding the casting by either hæmatite ore or manganese oxide, and exposing it to a red heat for several days or weeks, according to the size of the casting.

The strength of malleable iron is greater than the original strength of the cast iron from which it has been produced. It becomes slightly ductile, and its modulus of elasticity is raised. Mr. A. Martens gives the following average results of some tests on this metal, both for pieces which have been welded and for the unwelded metal:—

‡ MR. A. MARTENS' TESTS ON MALLEABLE CAST IRON. (AVERAGE.)

	Limit Stress. Tons per sq. in.	Maximum Stress Tons per sq. in.	Reduction in Area per cent.	Extension on 7·87 in. per cent.
Unwelded ..	4·44	16·38	8·2	2·5
Welded ...	—	19·24	13·3	1·1

The following results of tests on malleable cast iron are given by Mr. Ashcroft.§ Two sets of experiments were made, the first on material cast in 1884, and the second cast in 1885. These metals had respectively the following analysis :—

ANALYSES OF MALLEABLE IRON CASTINGS.

Constituents.	Cast in 1884. Per cent.	Cast in 1885. Per cent.
Total carbon	2·838	1·47
Carbon as graphite...	2·300	1·456
Sulphur	0·304	0·334
Phosphorus	0·259	0·222
Silicon	0·818	0·341

‡ Min. Proc. I.C.E., vol. lxxxviii., page 528.

The average results of the tests made are given in the following table :—

STRENGTH PROPERTIES OF MALLEABLE CAST IRON.

(ASHCROFT.)

	Cast in 1884.	Cast in 1885.
Tension.		
Elastic limit, tons per square inch	9·68	8·94
Maximum strength, tons per square inch	20·95	20·60
Elastic modulus, tons per square inch	10950·0	11620·0
Extension per cent. on 10in.	1·47	2·80
Compression.		
Area, square inches	0·361	0·361
Length, inches	2·959	2·928
Breaking stress, tons per square inch	21·15	21·60
Elastic modulus, tons per square inch	9680·0	1024·0
Bending.		
Coefficient of breaking strength, tons per square inch............	39·30	28·80
Elastic modulus, tons per square inch	13100·0	12330·0
Torsion.		
Torsion stress at limit, tons per square inch	8·35	8·93
Coefficient of torsional strength, tons per square inch	25·60	26·80
Coefficient of rigidity, tons per square inch	4220·0	4120·0

§ Min. Proc. I.C.E., vol. cxvii.

COPPER, ALLOYS OF COPPER, ALUMINIUM, TIN LEAD, ZINC.

212. Next to iron and its alloys, the most important metal in the arts at the present time is undoubtedly *copper*, either in its commercially-pure form or alloyed with other metals. Its chief advantages are its softness and malleability, its high heat-conducting properties, its non-corrodibility, and its high electrical conductivity. The tensile strength of copper is considerable, varying from six tons in castings to 16 tons per square inch for unannealed rolled bars. Copper and its alloys are annealed by heating to redness and cooling suddenly in water.

Alloyed with zinc, copper yields the useful metal *yellow brass*, which has a low tensile strength, and is only used for ornamental work, where strength is not required; and "Muntz metal," having a tensile strength of about 25 tons.

The group of *bronzes* consist of copper alloyed with tin and a little zinc, and give a tensile strength of from 10 to 27 tons, according to the mixture and manner of manufacture.

A small percentage (3 to 8) of aluminium added to bronze produces a metal of considerable ductility and very high tensile strength, this latter being from 25 to 40 tons per square inch.

The most striking characteristic of copper and its alloys from the point of view of the load-strain diagrams is the almost complete absence of a sudden yield point, such as is found in the irons, and the low elastic limit. Typical strain diagrams are shown in Figs. 190 and 191.

Aluminium is now produced fairly cheaply in the form of rolled bars, drawn rods, wire, sheet metal, angles, tees, and beams, as well as ingot metal for castings, the price being now between 1s. and 2s. 6d. per pound.

In the form of rods or bars, aluminium has a tensile strength of about 10 tons per square inch, accompanied by a fair amount of ductility.

The load-strain diagram for aluminium has the same peculiarity as iron at high temperature, it being found that the deformations take place in jumps, with the result of producing a stepped curve. (See Figs. 192 and 193.)

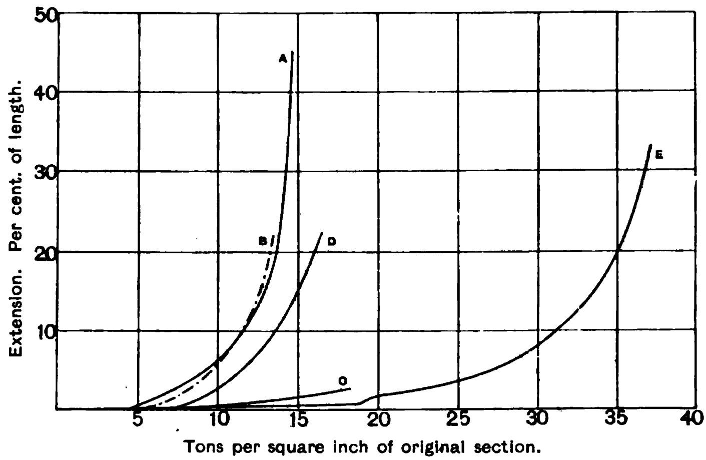


FIG. 190.—LOAD-STRAIN DIAGRAMS FOR TENSION.

A.—Rolled copper. B.—Yellow brass rod, annealed. C.—Yellow brass rod, unannealed. D.—Bronze. E.—Aluminium bronze.

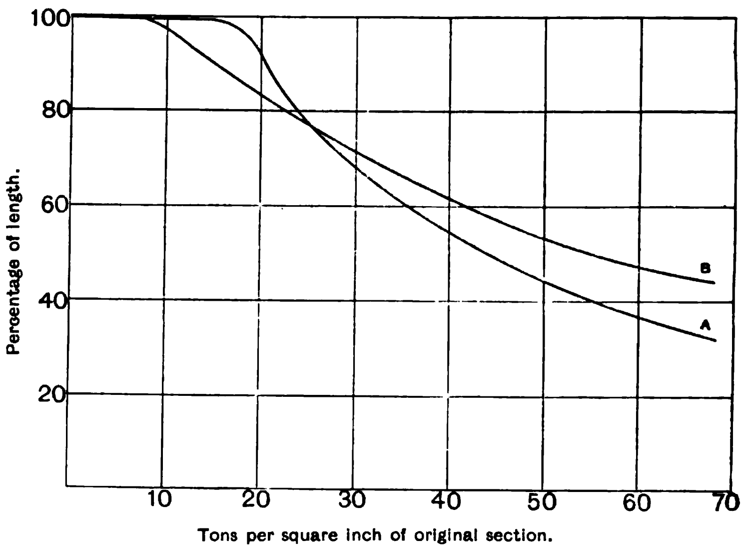


FIG. 191.—LOAD-STRAIN DIAGRAMS FOR SHORT COMPRESSION SPECIMENS.

A.—Copper. B.—Gunmetal.

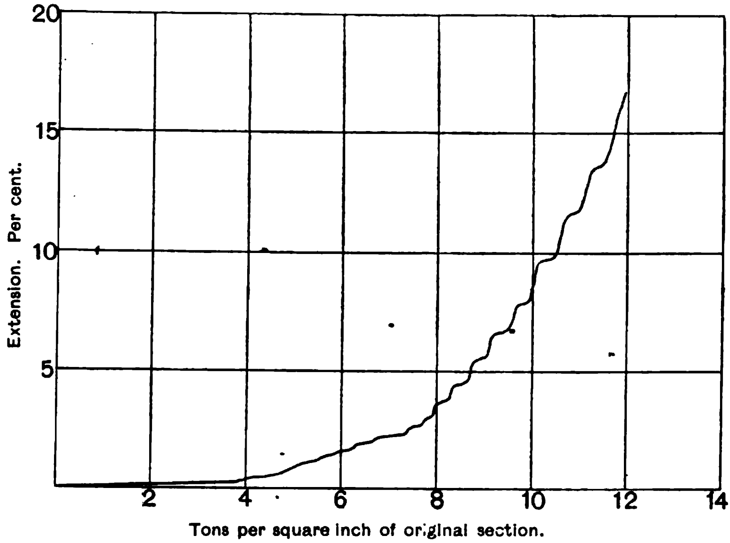


FIG. 192.—LOAD-STRAIN DIAGRAM FOR ALUMINIUM ROLLED BAR IN TENSION.

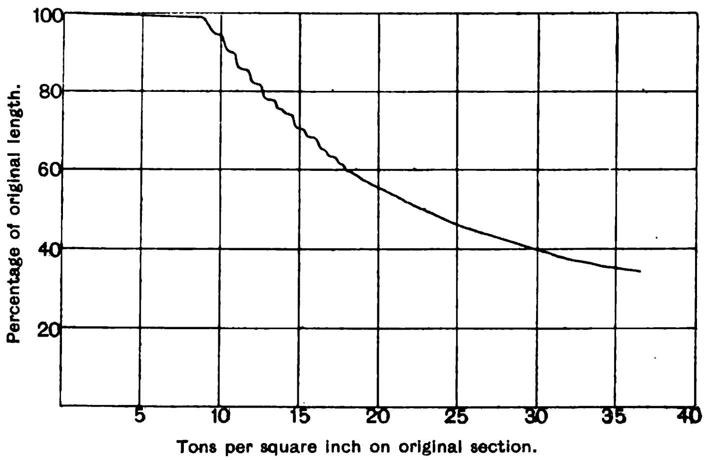


FIG. 193.—LOAD-STRAIN DIAGRAM FOR ALUMINIUM ROLLED BAR IN COMPRESSION.

In the following general table are given the chief strength properties of most of the above-mentioned metals :—

Material.	Tension. Elastic Limit. Tons per sq. in.	Tension. Max'm Stress. Tons per sq. in.	Tension. Elongation per cent	Tension. On Ins.	Tension. Reduction in Area per cent	Tension. E Tons per sq. in.	Compression. Elastic Limit. Tons per sq. in.	Compression. E Tons per sq. in.	Shear Stre'gth. f_S Tons per sq. in.	Ratio $\frac{f_s}{f_t}$	Torsion. f_{TE} Tons per sq. in.	Torsion. f_{T1} Tons per sq. in.	Torsion. f_{T2} Tons per sq. in.	Modulus of Rigidity.	Authority.
Copper, cast, very pure (av'ge of 4)	...	14·20	...	...	...	...	...	...	...	...	...	...	...	...	Anderson.
,, from bolts	...	16·00	...	...	...	...	...	...	...	...	...	...	...	...	
,, cast	...	6·5 to 9·2	...	...	...	4,460 to 6,700	...	...	...	...	...	...	...	...	Thurston.
,, ingot	...	11·6 to 13·3	...	...	...	...	...	...	...	...	...	...	...	...	
,, rolled	...	13·3 to 14·2	37 (mean)	8	...	...	...	...	...	...	...	...	...	...	Unwin.
,, hot rolled plate... ...	3·35	14·70	50	...	...	...	...	...	...	...	...	...	...	...	Johnson
,, cold hammered plate ...	8·90	14·70	30	...	...	...	...	...	...	...	...	...	...	...	
,, annealed bar ... about	3·90	14·0	40	10	57	7,000	4	...	10·5	0·75	...	...	...	...	
Gun metal bar, (copper, 64 ; tin, 8 ; and zinc, 2 parts)	7·25	13·68	...	...	...	5,060	...	...	12·47	0·91	5·40	15·80	11·85	2,500	Platt and Hayward
Gun metal bar, cast ... about	5·00	10·00	10	10	15	4,500	6	...	...	...	...	...	...	...	
Hard rolled bronze	...	26·90	...	...	...	...	...	...	16·06	0·59	...	...	...	...	Kirkaldy.
Gun metal from bronze guns average	6·56	12·19	...	...	...	...	...	...	...	...	...	...	...	...	Anderson.
Aluminium bronze (copper, 63 ; tin, $\frac{1}{8}$; zinc, $33\frac{1}{3}$; alum., $3\frac{1}{3}$)...	31·00	36·80	4	15	...	...	...	...	...	...	...	...	...	...	Johnson.
Aluminium bronze (copper, 92 ; tin, $\frac{1}{2}$; aluminium, $7\frac{1}{2}$) ...	9·00	26·40	18	15	...	...	...	...	...	...	...	...	...	...	
Aluminium bronze, rolled ...	24·00	40·00	35	15	...	...	...	...	...	...	...	...	...	...	
Aluminium, rolled bar ... about	7·0	10·0	6	10	29	5,000	9	...	6	0·60	...	...	...	1,680	
Phosphor bronze...	7·5	15·4	11·4	...	13	...	...	...	...	...	...	...	...	...	Kirkaldy.
Delta metal, rolled	22·9	33·3	11·0	8	50·4	5,945	...	...	...	...	...	...	...	...	Unwin.
Muntz metal, rolled (copper, 3 ; zinc, 2)	11·2	25·46	...	...	...	6,680	...	...	18·6	0·73	8·7	26·1	19·58	3,030	Platt and Hayward
Brass (copper, 2 ; zinc, 1) ...	...	12·9	...	...	...	5,130 to 6,580	...	...	...	...	...	...	...	...	Anderson.
Tin ... ... about	...	2	...	...	...	3,000	...	...	...	...	...	...	...	...	
Lead ... ... ,,	...	1	...	...	...	1,100	...	...	...	...	...	...	...	...	
Zinc ... ... ,,	...	2·5	...	...	...	3,100	...	...	...	...	...	...	...	...	

The following figures may be found useful:—

‖ BAUSCHINGER'S RESULTS.

	Elastic Limit.	Maximum Stress. Tons per square inch.	Contraction. Per cent.	Elongation. Per cent.
Zinc, cast.....	None found	1·670	3·1	0·35
" "	"	1·371	1·3	0·47
" "	"	1·517	1·3	0·12
" "	"	1.562	1·3	0·3
Zinc, sheet...	"	13·02	53	16·5 on 5·9in.
" "	"	11·17	53	9·9 "
" "	"	10·6	53	11·2 "
" "	"	10·41	61	20·3 "
Cast lead (average)	"	0·826	—	28 on 7·87in.

CHATELIER'S RESULTS (all at 60° Fah.)

	Maximum Stress. Tons per square inch.	Elongation. Per cent.
Cast brass..............	8·7	0·24 on 5·52in.
Tin bronze..............	10·1	5·7 "
Rolled brass...........	21·95	30·7 "

WIRES (PREECE).

	Maximum Stress. Tons per square inch.	Elongation. per cent.
Silicium bronze..........	27·6 to 50·0	About 2
Copper	28·4 " 30·3	" 1·5

¶ COEFFICIENTS OF ELASTICITY.

	Modulus of Elasticity. Tons per square inch.	Modulus of Rigidity. Tons per square inch.
Copper (bending tests)	7,400	2,960
Drawn copper wire (Wertheim)..........	7,600	—
Ditto, annealed.........	6,700	—
Copper (Savart).........	- -	2,660

‖ Bauschinger and Chatelier. Min. Proc. I.C.E., vol. cvii.
¶ Voigt. Min. Proc. I.C.E., vol. lxxv.

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